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The Economic Value of Improved Fuels and Fire Behavior Information

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ABSTRACT

An analysis of two routine fire management decisions on the Mount Hood National Forest provided insights into the appropriate expenditure levels for improving fuels and fire behavior information bases. In formulating the annual fire management budget request, improved information on fuel types is worth about one cent per acre per year, while the value of perfect fire intensity prediction is between one and five cents per acre per year. For complex decisions among alternative postharvest fuel treatments, reliable postharvest fuel loading estimates may be worth up to $800 for a 25-acre site.

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MANAGEMENT IMPLICATIONS

Many resource management decisions are based, in part, on estimates of forest fuel quantity, type, and condition. Existing and anticipated fuel conditions play a key role in predicting future wildfire activity and attendant impacts on management programs and resource outputs. Presumably, better information about fuels and fire behavior would enable land managers to make better fire management decisions and, thereby, improve the efficiency of fire management programs.

Improving information on fuels and fire behavior can be costly. It is necessary to balance the expected benefits with the costs of gathering or developing improved information. The value of new information depends upon many factors, the most important of which are the current level of information, the likelihood that new information will change decisions and, thereby, alter management actions, and the reduction in costs or losses accompanying a decision change. This report describes a quantitative analysis of the economic value of improved fuels and fire behavior information to fire managers and discusses the balancing of the economic value with the costs of such information. Although the specific models developed in this analysis are unique to the decisions and areas described, the general analysis approach can be useful in a large variety of resource management decision situations.

The analysis presented here spans the range of resolution requirements for fuels and fire behavior information by addressing the value of such information in the context of two decisions on the Mount Hood National Forest:

1. Formulating the annual fire management budget request at the national forest level or its equivalent—What is the most appropriate annual expenditure for wildfire protection on the forest?
2. A site-specific, fuel treatment decision—What is the most appropriate fuel treatment following harvest of a 25-acre stand? Alternatives include no treatment, prescribed burn, and intensive mechanical treatment.

In the analysis of each decision, the objective was to minimize management (or treatment) costs plus expected net resource value changes due to fire. No attempt was made to evaluate the ancillary benefits of wildland fuel information for making resource management decisions (e.g., site preparation, wildlife habitat management, and watershed management).

Budget Analysis Results

Over a wide range of cases, the expected value of perfect information on the distribution of fuel types for this decision was on the order of one cent per acre per year, which corresponds to about $10,000 per year for the entire Mount Hood National Forest. Note that this amount is the value of perfect information; that is, information that completely eliminates uncertainty. As such, it should be considered an upper bound on the value of new fuels information to the Mount Hood National Forest in the context of fire management budget decisions. This suggests that any forest-wide fuels inventory effort would not be economically justified for developing the annual fire management budget request. Funds invested in the development of an improved system of records-keeping (applicable to many national forests) to better utilize information already available (e.g., from timber stand surveys, fuel treatment activities, and other resource management activities) may be of greater value.

The expected value of perfect fire intensity predictions for wildfires was typically in the range of one to five cents per acre per year. While this is probably insufficient to merit any forest-specific research or detailed data gathering, it could justify continued research toward the development of improved models of fire behavior that would be of use on a number of forests.

A simple decision tree analysis was used to investigate the value of adding new fuel models to the existing set; that is, of providing a set of stylized fuel models with greater resolution. An additional model only rarely resulted in a changed decision; as a result, its availability had little value. This finding suggests that the resolution provided by the stylized fuel models now available is probably appropriate for formulating fire management budget level requests and may be appropriate for other forest-level fire management decisions.

Fuel Treatment Decision Results

Results of the analysis showed that for a wide range of assumptions the "no-treatment" alternative (which actually involves a small amount of hand treatment) was dominant, which leads to two possible conclusions:

1. Direct resource benefits of fuel (residue) treatment (such as for enhancing watershed, wildlife, or other resource values) are considerably in excess of those quantified in this analysis (i.e., the reduction of future wildfire losses).

2. Much more treatment activity is being carried out than is economically justified.

If the first conclusion is correct and some type of treatment must be carried out, the choice is between the prescribed burn alternative and the more costly but less uncertain intensive treatment.

Using the most likely scenarios, when the no-treatment alternative is inappropriate, the expected value of perfect information on postharvest fuel loading was approximately $300 to $800 for the 25-acre site (or $12 to $32 per acre). Information that could be expected to reduce uncertainty (perhaps reducing the variance of the probability distribution on the loading of fine fuels by 50-70%) would be worth $100 to $400 ($4 to $16 per acre). Accounting for all costs, this suggests that in many cases it would be worthwhile to invest one or two person-days in developing an improved estimate of postharvest fuel loading before making the final treatment decision.

Recommendations Based on the Mount Hood Analysis

1. For broad fire management planning and budgeting purposes, forest supervisors should consider forest-wide fuels inventory or fuels information management options which cost no more than two cents per acre annually.
2. The resolution provided by the sets of stylized fuel models now available should be considered adequate for evaluating alternative fire management budget levels.
3. Continued research to provide better understanding of fire behavior and budget effectiveness (the relationship between fire management activities and fire losses) appears to be justified.
4. Expensive fuel treatment following harvest does not seem to be justified in cases similar to that examined here if fire hazard reduction is the principal objective. More careful thought should be given to the no-treatment alternative in such cases.
5. Where other resource management objectives dominate the residue treatment decision (e.g., site preparation), and where broadcast burning is likely to be a good alternative but significant resource values may be sensitive to burning, it is probably worth investing on the order of one or two person-days per 25-acre cut-block in the improvement of the fuel information base prior to making the final treatment decision.

The above recommendations are applicable only in the context of the two types of decisions addressed in this analysis. They consider only the value of fuel and fire behavior information for evaluating the expected fire-related impacts of decision alternatives on resource outputs, and they are based on the current state of information available to Mount Hood National Forest managers, as related to the authors. These results may not be applicable to other types of fire management decisions or to management situations where the current state of information is substantially different from that described on the Mount Hood National Forest.

INTRODUCTION

Managers at all levels within the Forest Service and other land management agencies require estimates of fire behavior and expected losses or benefits from fire. At the highest levels, land use policy is affected by perceived fire hazards, as is fire protection planning, which is based on estimates of fire occurrence, behavior, and attendant damages or benefits. At the lower levels, tactical fire suppression decisions and site-specific fuel treatment choices utilize more precise fire behavior estimates. Information about the amount and character of wildland fuels plays a noteworthy role in all these decisions. Wildland fuels include aggregations of twigs, branches, stems, foliage, detritus, and other living and dead vegetative materials that occur on wildlands, either through natural processes or as a result of human activities. Fuel information quality affects the manager's ability to predict fire behavior and estimate fire effects, whether beneficial or detrimental. Just what quality of information is needed for various management activities, in terms of accuracy and resolution, is not well known.

This report describes a case study to determine the economic value of improved information about the quantity and properties of wildland fuels. Presumably, better fuels information would enable forest managers to improve the efficiency of fire management programs. The value of improved fuels information depends upon many factors, the most important of which are the current level of information, the probability that new information will result in changed decisions, and the expected change in costs and resource values resulting from those decision changes. This case study explicitly addresses these factors and estimates the maximum value of new fuels information on a dollar-per-acre basis.

The area chosen for this case study comprises two ranger districts of the Mount Hood National Forest, Clackamas and Estacada, covering about 400,000 acres of the western slope of the Cascade Mountain Range near Portland, Oreg. The areas are heavily forested with commercially valuable Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). About $6,000,000 worth of commercial sawtimber is harvested from the two districts each year (600 acres). The fuel treatment and fire suppression budget for the districts was $743,000 in 1978, and wildfires burned an average of about 200 acres each year from 1970 to 1978. The resulting annual fire losses averaged about $1,200 per acre or $240,000 per year for the two districts.

This case study concentrated on determining the value of fuels information in the context of two clearly recognizable decisions:

1. The forest-level, annual, presuppression fire management budget request decision.
2. A site-specific, postharvest fuel treatment decision.

Based on each of these decisions, managers allocate a substantial amount of money annually in an effort to reduce fire losses. The alternatives, outcome measures, and major uncertainties for each decision are summarized in table 1.

Fuel information is useful in the budget request decision as an aid in estimating fire hazard and the potential effectiveness of money spent preventing and managing wildfires. Presumably, the budget will be too small if the expected fire hazard is underestimated and too large if it is overestimated. Fuel information is useful in the site-specific, fuel treatment decision as an aid in estimating the effects of a prescribed fire as well as the postharvest fire hazards associated with different treatment methods.

These two decision classes span most of the range of precision requirements for fuel-related fund allocation decisions at the forest level. While the budget decision is large, it is made only once a year. The annual budget for fire prevention, presuppression, and initial attack was about $266,000 in 1978 for the Clackamas and Estacada districts. (An additional $477,000 was budgeted for treating the fuel associated with current and past logging operations. The bulk of these latter funds is from timber sale collections.) The site-specific, fuel treatment decision is much smaller, involving expenditures from $2,500 to $32,500 for a 25-acre site, depending upon the treatment chosen. However, roughly 25 fuel treatment decisions of this type are made each year on the Clackamas and Estacada districts.

The object of this report is to provide insight into the role of fuel information and its approximate value within two specific decision contexts on the Mount Hood National Forest—not to derive a precise single number that expresses the total value of additional fuel information. Details of the two analyses are presented in separate sections, following an explanation of the analytical approach used to estimate potential information value.

ANALYTICAL APPROACH

The economic value of wildland fuel information is calculated by estimating the impact that improved information has on fire losses or benefits and management costs. This section contains an overview of the forest level budget decision and how it might be affected by fuel information. An illustrative calculation of the expected value of perfect information (EVPI) is also included in this section to provide an understanding of how the economic value of information is determined. A more practical treatment of the budget request decision and actual calculations for the Mount Hood case study are presented subsequently.

Ideally, the fire management budget is established at a level that minimizes the combined management costs and net resource value changes caused by wildfire (NVC). In this formulation, positive NVC values represent net resource damages, while negative values represent net benefits. The historical development of this criterion, along with other fire management objectives, is traced by Gorte and Gorte (1979). Affected values may include wildlife, watershed, and recreation values, as well as timber values and improvements. The optimal budget level is illustrated in figure 1. Identifying the optimal budget would be straightforward if the relationship between presuppression expenditures and suppression costs plus NVC were known as indicated in the figure. The budget decision is complicated, however, by the fact that this relationship is highly uncertain. The major contributors to this uncertainty are the number and location of fires in the coming year, fuel conditions, weather, fire behavior, fire effects, and the effectiveness of presuppression expenditures (budget effectiveness).

The object of this case study is to estimate the economic value of reducing several of these uncertainties by improving information available to the decisionmaker. To illustrate the methodology, suppose that the only uncertainties are fuel conditions and budget effectiveness. Suppose, also, that the budget decision is simplified to two distinct alternatives: increase the budget by 10% or maintain the current level. This decision, the subsequent uncertainties, and the outcomes (cost plus NVC) are diagramed in decision-tree form in figure 2. As indicated in the diagram, there are two

Table 1.—Summary of decisions addressed in this study

	Decision alternatives	Outcome measures	Major uncertainties
Annual fire management budget request decision	Continue current budget level Increase budget Decrease budget	Fire management costs Fire effects (resource value changes from wildfires)	Aggregate fuel characteristics Fire intensities given fuel characteristics Budget effectiveness
Fuel treatment decision	No treatment Prescribed burn YUM 6×6[1]	Posttreatment fire hazard Losses to residual stand	Postharvest fuel characteristics Prescribed fire intensity Treatment effects (fuel reduction and damage to residual stand)

[1] *YUM 6×6 stands for Yarding Unmerchantable Material—all material exceeding 6 feet long by 6 inches in diameter.*

possible fuel situations: 100% of the area is represented by stylized fuel model 10 or 100% of the area is equivalent to model 8. These stylized fuel models are described by Albini (1976). Model 8 (closed timber litter) implies a fuel loading of about 15 tons per acre (fine fuels), while model 10 (timber litter plus understory) represents a loading of about 30 tons per acre.

Assume that the entire planning unit is covered with the same fuelbed and that there is a probability of 0.5 that the fuel is described by fuel model 8. If the increase-budget alternative is selected, and model 10 turns out to be most representative of the fuel, there is an equal chance that the budget increase will result in a 10% or 20% reduction in the number of escaped fires. For the same alternative, model 8 implies an equal probability of a 10% decrease or no change in escaped fires.

Hypothetical outcome costs are broken down into three classes—presuppression, suppression, and NVC—and are itemized at the tip of each branch. Suppression costs are proportional to NVC.

Tracing one path through the decision tree, the upper path denotes a choice to increase the budget by 10%, the fuelbed is most closely characterized by model 10, and the effect of the 10% budget increase is 20% reduction in escaped fires. This scenario results in $110,000 in presuppression costs, $40,000 in suppression costs, and NVC of $120,000. The probability that this outcome will occur is 0.25 if the increase-budget alternative is chosen.

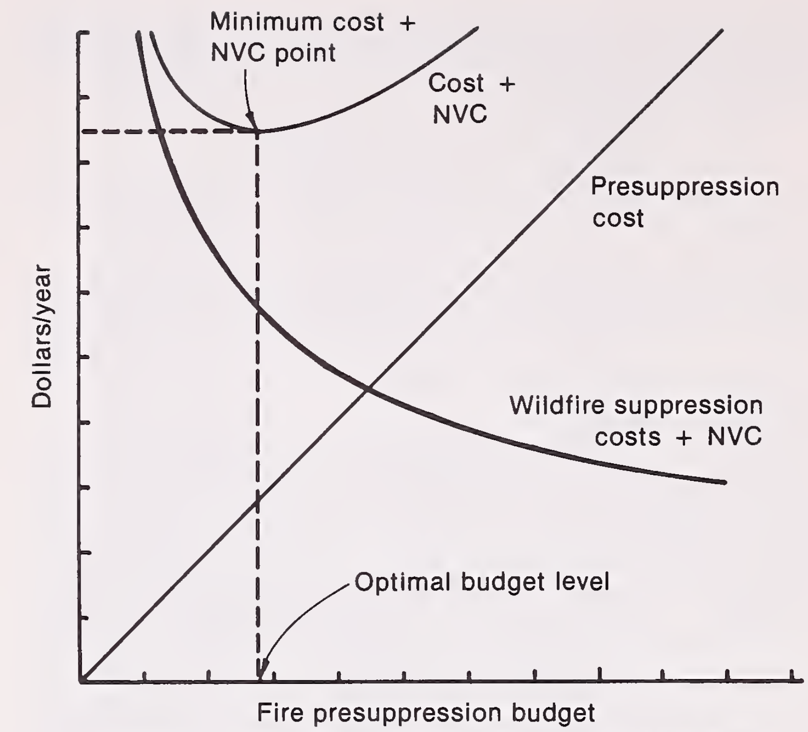


Figure 1.—Determination of the optimal budget level.

Given the uncertainty and cost structure of the example, the expected cost plus NVC is lower for the increase-budget option—$228,000 versus $235,000 for the no-increase option. (The term "expected cost plus NVC" is used here in the statistical sense. It is the sum of the probability of each outcome times its overall cost; e.g., 235 = 0.5 × 300 + 0.5 × 170.) Assuming that minimizing the expected net cost is the basis for

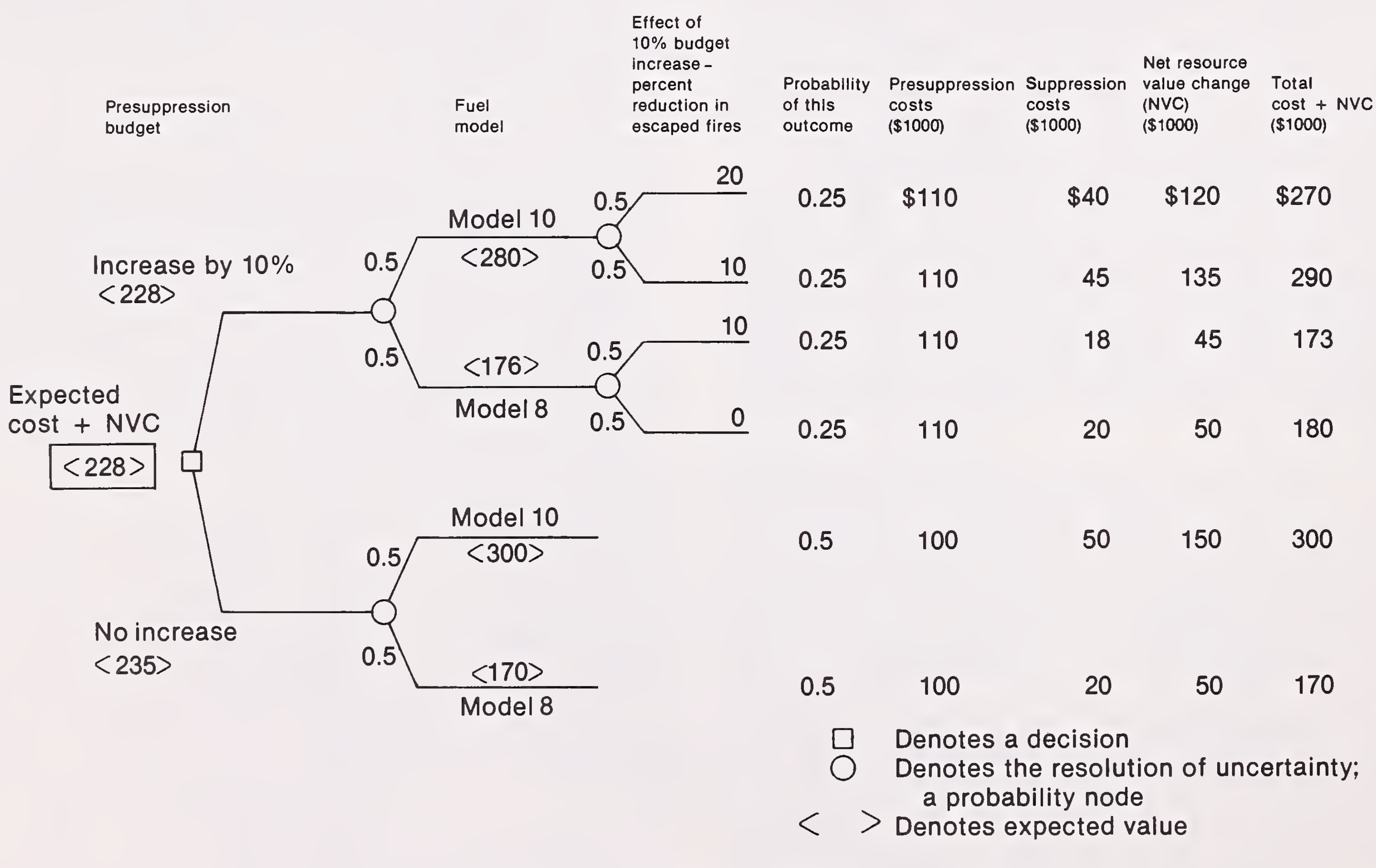


Figure 2.—Presuppression budget decision.

the decision, the increased budget alternative is preferred in this example.

What would it be worth to know precisely whether model 8 or model 10 is the right choice before making the budget decision? In other words, how much should we be willing to pay a clairvoyant to look into a crystal ball and tell us which fuel model is appropriate? By a simple example, we can calculate the expected value of the information by rearranging the tree to represent the sequence of events when fuels information is known before the decision is made. This situation is diagramed in figure 3. The model 10 probability is still 0.5 from our perspective, but at the time the decision is made, it is either 1 or 0, depending on whether the clairvoyant says "8" or "10." If the clairvoyant says that model 8 is appropriate, we would change our choice and maintain the current budget, because under these circumstances the expected cost plus NVC is lower ($170,000 rather than $176,000) at the current budget level. If we knew for sure that model 10 was appropriate, we would increase the budget. The expected cost for this choice is $280,000. The arrows in the diagram denote the lowest cost alternative at each decision node.

We should be willing to pay up to $3,000 for perfect information on fuel conditions before making the budget decision. This amount is the difference between the expected cost with prior information from figure 2 ($228,000) and the expected cost with perfect information from figure 3 ($225,000).

Another way of looking at this is illustrated in figure 4. Here the decision tree is redrawn to make it ap-

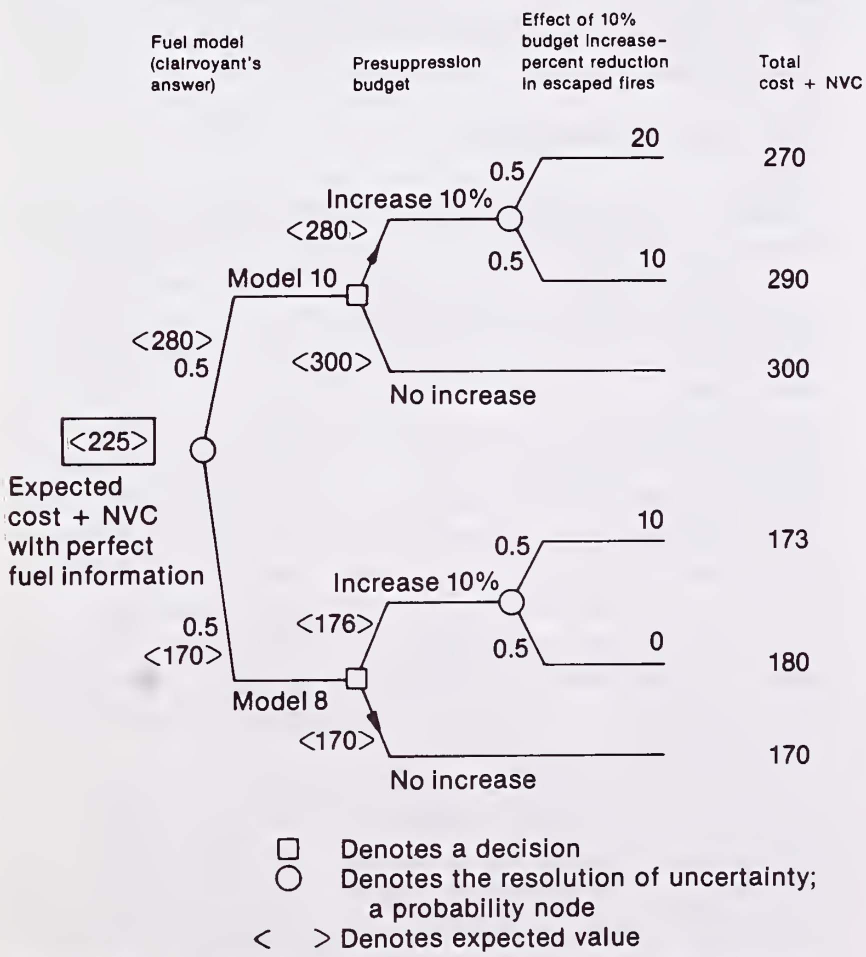


Figure 3.—Calculation of expected cost plus NVC with perfect fuel information.

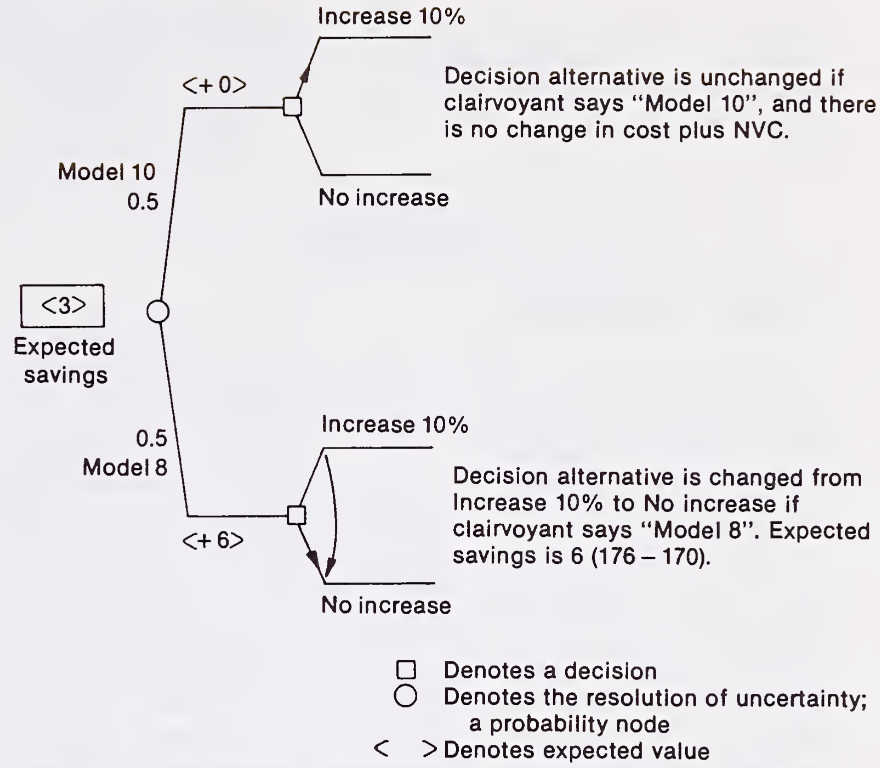


Figure 4.—Calculation of expected savings from perfect information.

parent how the expected cost savings result from the clairvoyant's perfect information. Briefly, if the clairvoyant says "model 8," our choice is changed from an increase of 10% to no increase and the resulting expected savings are $6,000 (176-170). If the clairvoyant says "model 10," the decision does not change and the expected cost plus NVC is unchanged. The probability that the clairvoyant will say "model 8" and save us $6,000 is 0.5; therefore, the expected savings is 0.5 times $6,000 or $3,000, which matches the previous value of perfect information calculation. For further discussion of this procedure, refer to Howard (1966) and North (1968).

Although perfect information is not attainable in practice, the expected value of perfect information is useful because it provides an upper bound on what one should be willing to pay for any level of fuel information in the context of a single decision or class of decisions. The perfect information concepts are used in the following sections to provide insight into the value of fuel inventory or modeling efforts. The value of information is estimated under a broad range of conditions to test the utility of the estimates in varying field situations.

THE FIRE MANAGEMENT BUDGET REQUEST

This section examines in detail the decision made by the management of a national forest in requesting a budget level for fire protection activities. The specific decision evaluated in this section of the case study is the overall fire management budget level for the Clackamas and Estacada districts of the Mount Hood National Forest. Some insights were also gained concerning the allocation of the overall budget among the various fire management activities. Although the

details reflect these two districts uniquely, many of the insights and conclusions are applicable to the entire Mount Hood National Forest and, in fact, to many national forests.

The Decision

Nature of the Decision

Each year every national forest supervisor must submit a budget request for the fiscal year beginning 2 years hence. Typically, work plans for individual districts are aggregated by forest staff to produce tentative budget requests by management activity. These are reviewed, modified, and consolidated by the forest supervisor to produce a fully specified budget request for the forest, which is subsequently reviewed and frequently modified by higher levels of the Forest Service, the Department of Agriculture, the Office of Management and Budget, the President, and Congress.

The fire management component of the annual budget request identifies funds allocated to wildfire prevention, detection, maintenance of initial attack forces, maintenance of air support forces, and fuel management. Wildfire suppression costs have generally been accounted for separately. This case study will focus on the decision made by the individual national forest staff in attempting to formulate and justify an optimal budget request for wildfire protection activities.

Budget Optimization

The optimization of fire management expenditures has been a subject of continued practical and academic interest throughout the history of organized wildfire protection in the United States (Pyne 1981). The theoretical development and application of economic models and criteria related to this task are discussed by Gorte and Gorte (1979). Mills[4] examines and compares three approaches to identifying financially optimum levels of fire protection for wildland resources—cost + NVC, benefit/cost ratios, and present net worth.

Since enactment of the Renewable Resources Planning Act (RPA) and the National Forest Management Act (NFMA), there has been a marked upsweep of interest in determining the economic efficiency of fire management programs. Prompted by escalating fire management costs during the early 1970's, the Office of Management and Budget asked the Forest Service in 1975 to account for increasing expenditures and to identify which fire management practices are best in terms of costs and results.[5] The Forest Service response (U.S. Department of Agriculture, Forest Service 1977) documented real program cost trends over the period 1965 to 1975, but those preparing the response were unable to identify which practices were best. As a result, the Forest Service initiated a study to analyze the economic efficiency of fire management programs on six national forests representing a range of fire management situations throughout the nation (Schweitzer et al. 1982). Results indicated that the initial attack and aviation operation budgets on four of the six forests should be reduced by 20% in order to minimize expected cost plus NVC. Similar methods were later extended to a study of 41 national forests (U.S. Department of Agriculture, Forest Service 1980a), where results were aggregated nationally. The latter analysis indicated that minimum cost plus NVC for Fiscal Year 1980 could be achieved by increasing the National Forest System's fire protection budget by 13-20% over the FY 1979 level. Methods and criteria from both of these studies have been incorporated in a Forest Service Handbook procedure for analyzing fire management programs within the context of forest planning (U.S. Department of Agriculture, Forest Service 1980b). Mills (1979) describes ongoing research to refine these procedures and further develop management guidelines for economic evaluation of fire management practices.

The present analysis of the Mount Hood National Forest budget decision focuses on determining the expected value of improved information for optimizing the fire management budget request; it is not concerned with actually identifying the optimum budget level. Analytical models and procedures, therefore, differ somewhat from those used in previous fire management budget analyses.

Definition of Outcomes

Under the cost-plus-NVC criterion for determining the optimal budget level the objective is to minimize the sum of fire management costs and NVC caused by the fires and fire-associated activities. The cost side is reasonably clear. For a given year, uncertainty is introduced only by the possible range of expenditures for fire suppression. The resource value changes are more difficult to determine. Most easily measured are the timber value changes and costs of rehabilitation. Less easily quantified are watershed, recreation potential, visual amenities, and other resource values. The fact that many of these benefits or damages are often difficult to measure and equally difficult to put into economic terms does not lessen the need for considering them when analyzing forest management decisions (Daniel and Zube 1979).

One way to represent the decision is outlined in figure 5. The decision itself is shown at the bottom of the figure, while important uncertainties are shown at the left. The decision alternative selected, the uncertain factors, and the forest system interact to result in a set of outcomes, which are the factors a decisionmaker would like to know to evaluate the consequences

[4]*Mills, Thomas J. Calculation of financial return and determination of budget levels for fire protection programs. (Manuscript in preparation). U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.*

[5]*Lynn, James T. 1975. Letter to Honorable Earl Butz, Secretary of Agriculture. April 15, 1975. Executive Office of the President, Office of Management and Budget, Washington, D.C.*

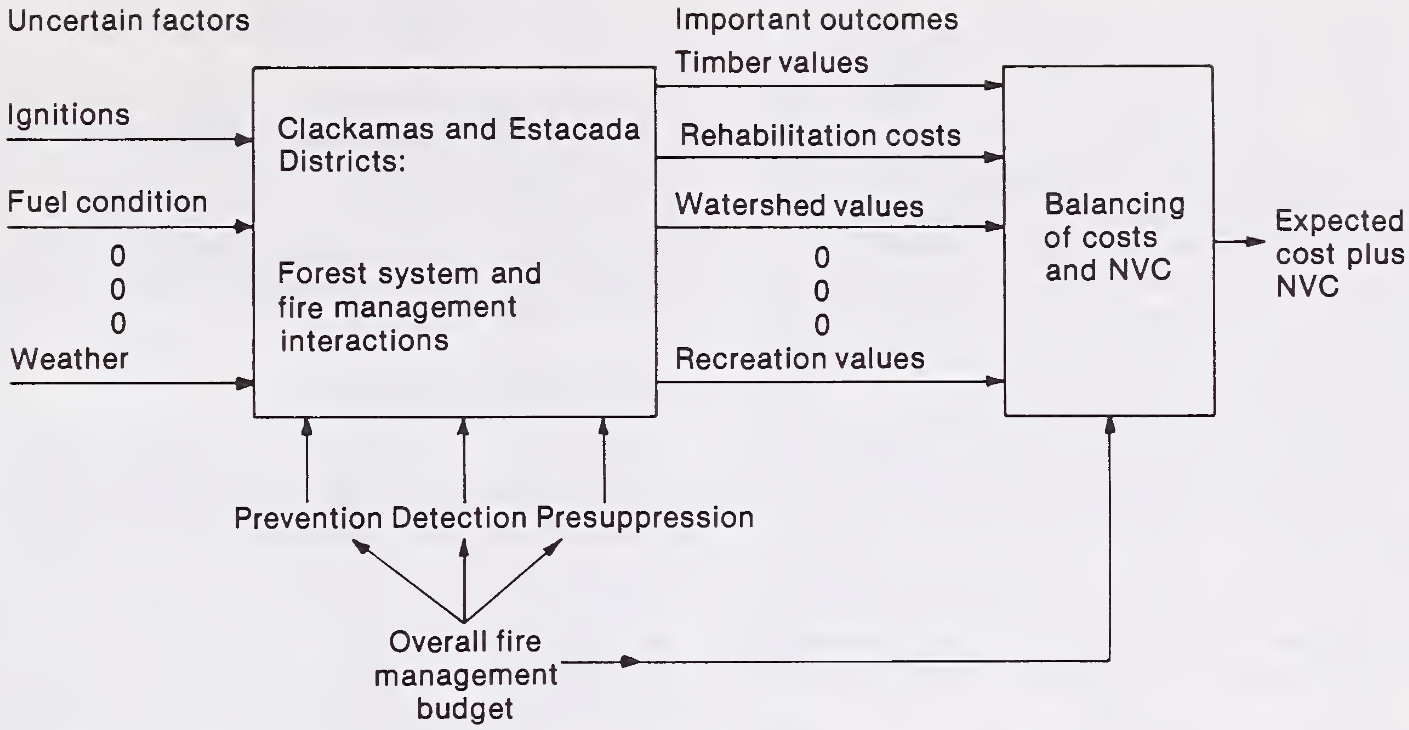


Figure 5.—Budget decision outline.

of the decision. The outcomes are assigned values and are added with the management costs to produce an expected cost plus NVC.

Representation of Uncertain Factors

Preliminary sensitivity analyses identified fuel conditions and the resulting fire behavior as among the most critical uncertain factors affecting the budget level decision. Uncertainty in fire effects and resource values was also important. These elements were treated parametrically, in an effort to model and analyze the budget request decision. This approach allows comparison of decision alternatives over a wide range of possible values. Uncertainty in the effectiveness of budget expenditures was also important and was treated separately. (Effectiveness is measured as the reduction in fire losses associated with an increase in the budget.) Part of the uncertainty in predicting fire intensity reflects uncertainty in future weather conditions. However, the aggregate nature of the budget request decision, involving broad areas over a full fire season, allows adequate representation of weather variations using archived local fire weather observations (Furman and Brink 1975). Similarly, local fire occurrence data (Roussopoulos et al. 1980) provide a useful means of representing variations in annual fire occurrence patterns.

Fuel Conditions.—For modeling a decision at the aggregate level of the overall fire management budget, the stylized fuel models described by Albini (1976) provided a starting point to represent fuel loading and characteristics. A simple analysis, described later in this section, yielded estimates of the value of developing a more detailed set of stylized fuel models (i.e., more models, thus providing greater resolution). Mount Hood National Forest fuels and fire management staff felt that 4 of the 13 available models will adequately describe the fuels conditions of the Clackamas and Estacada districts. These were model 10 (timber litter and understory), model 8 (timber litter), model 13 (heavy slash), and model 12 (medium slash). Fuel and fire specialists on the Mount Hood National Forest were uncertain as to how the total area should be allocated among the four stylized models. The uncertainty was reflected in varying estimates by Mount Hood staff of the fraction of the total case study area that should be represented by each fuel model. For example, the estimated area to be represented by slash models 12 and 13 ranged from 5% to 30% of the total. The range of uncertainty is defined explicitly later in this section. Note that some of this uncertainty is due to the approximate nature of the stylized fuel models. A typical uncertainty was whether to represent an area with brush, some old slash, and partial timber as a model 12 type or a model 10 type. A working paper prepared in the early phases of this study discusses in more abstract terms some of the implications of using stylized fuel models and provides some insights on when it may be more appropriate to use direct assessment of fuel loading rather than stylized models.[6]

Fire Behavior.—For this analysis, fire behavior was represented by the fireline intensity (Byram 1959). Intensities used were calculated using the FIREBHV program described by Hirsch et al. (1981), which integrates historical fire records (Roussopoulos et al. 1980), fire weather station records (Furman and Brink 1975), and stylized fuel models (Albini 1976) with the Rothermel fire behavior model (Rothermel 1972) to generate cumulative probability distributions for fireline intensity. The uncertainty represented by the cumulative distribution reflects variation in weather. Probability distributions were produced for each fire weather station in or adjacent to the Clackamas and

[6] *Barrager, Stephen M., and David Cohan. 1979. Fuel information alternatives and fire behavior uncertainty. (Unplublished report on file at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)*

Estacada districts and for each stylized fuel model appropriate to the area. (A sample run is included in the appendix.) The distributions for the several fire weather stations were averaged to produce a single probability distribution for each stylized fuel model. Resulting probabilities for the three intensity classes recognized in this study are listed in the appendix.

An additional source of uncertainty is introduced by the necessarily approximate nature of the fire behavior model itself. The representation of this uncertainty is discussed later in this section.

Although we have attempted to separate the effects of fuel uncertainty from fire behavior uncertainty, it is important to note that the two are intimately related. Uncertainty in fuel conditions is one of several factors that contribute to fire behavior uncertainty. The distinction is made in this analysis to allow assessment of the relative importance of better fuel information in reducing the overall uncertainty regarding fire behavior.

Fire Size.—Even when one can assume that a particular fuel model is applicable and when weather conditions and fire behavior are known, there is still considerable uncertainty as to the final size of a fire. This is due to the actual spatial variations in fuel load and characteristics, topography, effectiveness of suppression activities, and other factors. Uncertainty in fire size given fire intensity and other factors was captured by probability encoding of expert opinion during a series of interviews and discussions with Mount Hood National Forest staff and will be discussed later.

Decision Tree Representation

Figure 6 shows a generalized decision tree representation of the fire management budget request decision and important uncertain factors. The box represents the decision, and the lines emanating from it represent decision alternatives. The circle nodes represent the uncertain variables. In this tree the decision and uncertainty, or chance, nodes are not connected. This convention is a shorthand representation of the tree where each node is connected to all branches of the preceding node.

The Cost-Plus-NVC Model

A simple quantitative model was developed to calculate fire management cost plus fire-induced, resource-value changes under various assumptions. The model is intended to provide a consistent framework for comparing alternatives and analyzing sensitivities. Its results should not be interpreted as precise predictions.

Overall Model Structure

The model is composed of a number of submodels, as shown in the block diagram of figure 7. The ignitions submodel divides ignitions into three classes by cause: industrial, other human-caused, and lightning. The nominal, or long-run, expected number of ignitions in each class is adjusted to reflect changes in prevention activities. In many of the model runs documented in the following section, the ignitions submodel was not used. The expected number of ignitions in each class, given prevention activities, was assessed and input directly into the fire location submodel. In a more detailed model, ignitions in each class might be expressed as a function of prevention or fuel treatment expenditures. The breakdown of annual ignitions used for most model runs (reflecting long-term averages based on Form 5100-29, Individual Fire Report data, adjusted for recent prevention activities) consisted of 1 industrial ignition, 25 other human-caused ignitions, and 8 ignitions caused by lightning.

The fuels submodel reflects the allocation of the total area (in this case, of the Clackamas and Estacada districts) to the appropriate stylized fuel models. This breakdown drives the fire location submodel. The nominal assignment of area to the fuel models was 280,000 acres to fuel model 10, 80,000 acres to model 8, and 20,000 acres each to the models 12 and 13. These values are the medians of the estimates provided by the Mount Hood National Forest staff.

The fire location submodel assigns ignitions to area types (each area type being represented by a stylized fuel model). All industrial ignitions are assumed to oc-

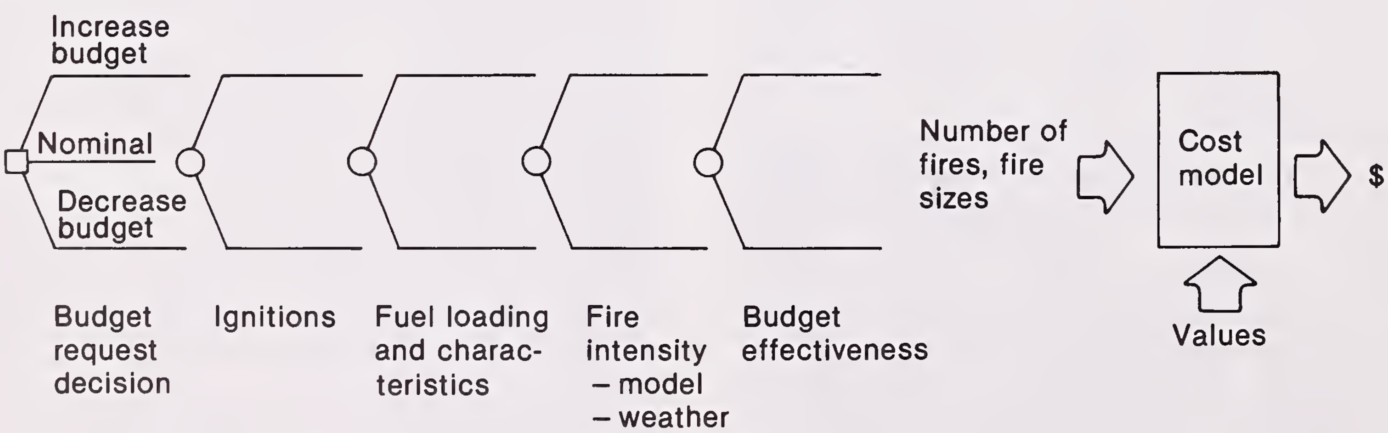


Figure 6.—Generalized decision tree for budget request decision.

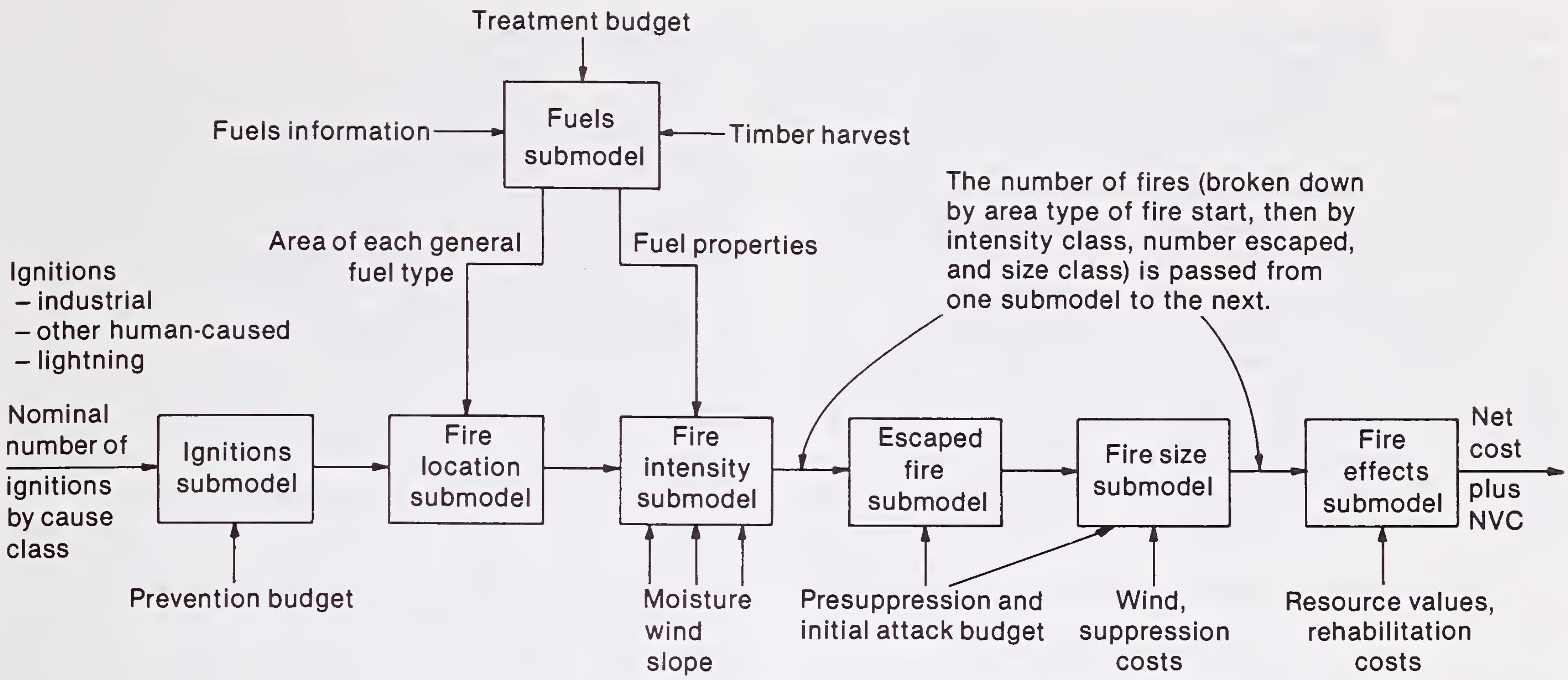


Figure 7.—Cost-plus-NVC model block diagram.

cur in slash areas. Other human-caused and lightning-caused ignitions are allocated to the area types in proportion to the number of acres assigned to each area type. It is possible that a greater proportion of lightning ignitions occur in model 8 areas, since such areas typically are at higher elevations. This would imply a shift of, perhaps, one or two ignitions per year from model 10 to model 8. Such a change would cause the model results to change by only a few percent. Using the nominal (base case) data for fire occurrence and fuel model area, the expected number of ignitions per year is about 23 in model 10 areas, 7 in model 8 areas, and 2 in each of the slash types (models 12 and 13).

The fire intensity submodel takes as input the number of fires in each area type and assigns the fires to intensity classes. Intensity classes used for most of the analyses were the following:

Intensity class	$Btu \cdot foot^{-1} \cdot second^{-1}$
Low	0–100
Medium	100–700
High	> 700

An intensity of 100 $Btu \cdot foot^{-1} \cdot second^{-1}$ is about the limit beyond which people are unable to work at the fire edge. At about 700 $Btu \cdot foot^{-1} \cdot second^{-1}$, spotting begins to be a problem and the limit of direct attack is reached. The basis for allocating the fires to intensity classes is a set of discrete approximations to the cumulative probability distributions generated by the FIREBHV computer program discussed previously. A discrete distribution is used for each area type (that is, for each stylized fuel model). For example, for the medium slash (model 12) stylized fuel model, there is a 3% chance of a low-intensity fire, a 61% probability of a moderate-intensity fire, and a 36% chance of a high-intensity fire. The complete distributions are listed in the appendix. Over all fuel types, one might expect about 25 fires per year in the lowest intensity class, about 6 in the intermediate class, and 3 in the highest intensity class.

The escaped fire submodel divides all fires (broken down by area type and intensity class) into those that are controlled by initial attack forces and those that escape initial attack. Escaped fires are defined to include those that are controlled by initial attack forces at a size exceeding that of the two lower size classes (nominally, greater than 20 acres) as well as those escaping initial attack efforts and requiring reinforcements. The fraction of fires escaping depends upon the area type (fuel conditions) and fire intensity class and is also affected by expenditures for presuppression activities and fuels treatment. The nominal escape fractions used in this analysis were based on the judgment of Mount Hood National Forest fuels and fire management staff, using the encoding method of Spetzler and Stael von Holstein (1975) and calibrated so that the model results reflect historical experience.

The fire size submodel divides the fires into the size classes of 0-1 acres, 1-20 acres, 20-200 acres, and greater than 200 acres. The fraction of fires assumed to be in each size class is a function of area type, intensity class, and whether or not the fires escaped initial attack. The fractions can be interpreted as a discrete probability distribution over fire size (conditional on intensity, stylized fuel model, and escape status). The distributions used were developed in cooperation with Mount Hood National Forest staff. The final distributions (listed in appendix) were developed through an interactive process of encoding experienced judgment and examining the quantitative implications (Spetzler and Stael von Holstein 1975).

The fire effects submodel assigns costs and resource value changes associated with fires. A table is entered giving the per-acre fire effects, such as changes in timber value and rehabilitation costs in thousands of dollars as a function of area type, intensity class, and size class. A typical cost was $1,000 per acre. The full table of costs is included in the appendix. For each fire category, the per-acre NVC is multiplied by the aver-

age size of fires in that size class. Total expected annual NVC is then calculated by multiplying these values by the number of fires in each category and summing over all size classes, intensity classes, and area types. Suppression costs are calculated in a similar manner. Nominal supression costs were assumed to be $500 per acre (except for the smallest size class). These values are then added to the fire management budget, resulting in the total annual cost plus NVC.

The general flow of the cost-plus-NVC model is to start out with the expected annual number of ignitions and break them down by location, intensity of the resulting fires, and fire size, as diagramed in figure 8. Since the effects of fires are generally not linear with size or intensity, the detailed breakdown allows fire damage costs to be assigned in a consistent manner.

The model equations can be summarized as follows:

$$IG(i) = \sum_j PR(i, j) \times IG(j)$$

where:

$IG(i)$ = the annual ignition rate in area type i (represented by fuel models 8, 10, 12, and 13),

$PR(i, j)$ = the fraction of ignitions from source j (industrial, other human-caused, or lightning) that occur in area type i,

$IG(j)$ = the annual number of ignitions from source j.

$$\text{Expected Total NVC} = \sum_i \sum_k \sum_l \sum_m IG(i) \times INT(i,k) \times ESC(i,k,l) \times SIZE(i,k,l,m) \times NVC(i,k,m)$$

where:

$INT(i, k)$ = probability of intensity class k given area type i,

$ESC(i, k, l)$ = probability of escape status l (yes or no) given area type i and intensity class k,

$SIZE(i, k, l, m)$ = probability of size class m given area type i, intensity k, and escape status l,

$NVC(i, k, m)$ = per acre net resource value change given area type i, intensity class k, and size class m.

$$\text{Expected Total Cost} + \text{NVC} = \text{Expected Total NVC} + \text{Budget Cost}$$

Base Case Data

Data were developed in cooperation with staff from the Mount Hood National Forest. Both historical records and judgment based on on-site experience were used. Data used for the cost-plus-NVC model base case are listed in the appendix.

Base Case Results

Base case results are listed in tables 2a and 2b. Table 2a gives a complete summary, while the detailed results broken down by the type of area in which a fire starts are listed in table 2b. The expected number, size distribution, and total burned area of fires calculated for the base case very closely reflect recent experience on the Clackamas and Estacada districts. The numbers are not meant to represent any particular year, but rather a long-term average. The results are based upon a fire management budget at roughly current levels, totaling about $743,000 for the Clackamas and Estacada districts, of which $477,000 is for fuel treatment.

Of the average of 34 annual ignitions, about 28 are expected to be controlled at a very small size. Fires reaching an average size of 10 acres occur at an average rate of roughly five per year. One might expect a fire in the 100-acre class once every one to two years and a very large fire (of approximately 1,000 acres) about once every 15 years. Note that these are to be interpreted as long-run averages. The occurrence of a large fire in any given year does not imply that several years must pass before another is possible.

Examination of the base case summary results leads to some interesting observations. Fires in the highest intensity class lead to over 60% of the net resource damages, although the expected number of such fires is only about three per year. It is reasonable that the most intense fires have the greatest chance of burning over a large area and of having the greatest effect on timber and other resources. Although only about 13% of the fires start in areas best represented by slash stylized fuel models, such fires account for over 47% of all fire damage costs. It follows directly that fires starting in slash have a greater chance of reaching higher intensities than do those starting in timbered areas. Fuel model 8 is almost "fireproof" under the weather conditions of the Mount Hood National Forest. All fires in areas represented by this model were in the lowest intensity class, resulting in insignificant resource value changes.

Sensitivity Analysis

Sensitivity analysis serves two purposes. Its primary intent is to identify which of the many uncertain parameters are critical to a given decision. This identification allows the uncertainty in the variables to which the decision is most sensitive to be represented explicitly by a probability distribution. Such a representation is prerequisite to any calculations of the economic value of improved information. The second purpose of sensitivity analysis is to provide insight into the behavior of the system. This was particularly useful in the analysis of the fire management budget-request decision.

Because we are not concerned with actually identifying the optimum budget level for the two districts, it is not necessary to specify fully the quantitative relationship between the budget level and expected NVC (i.e.,

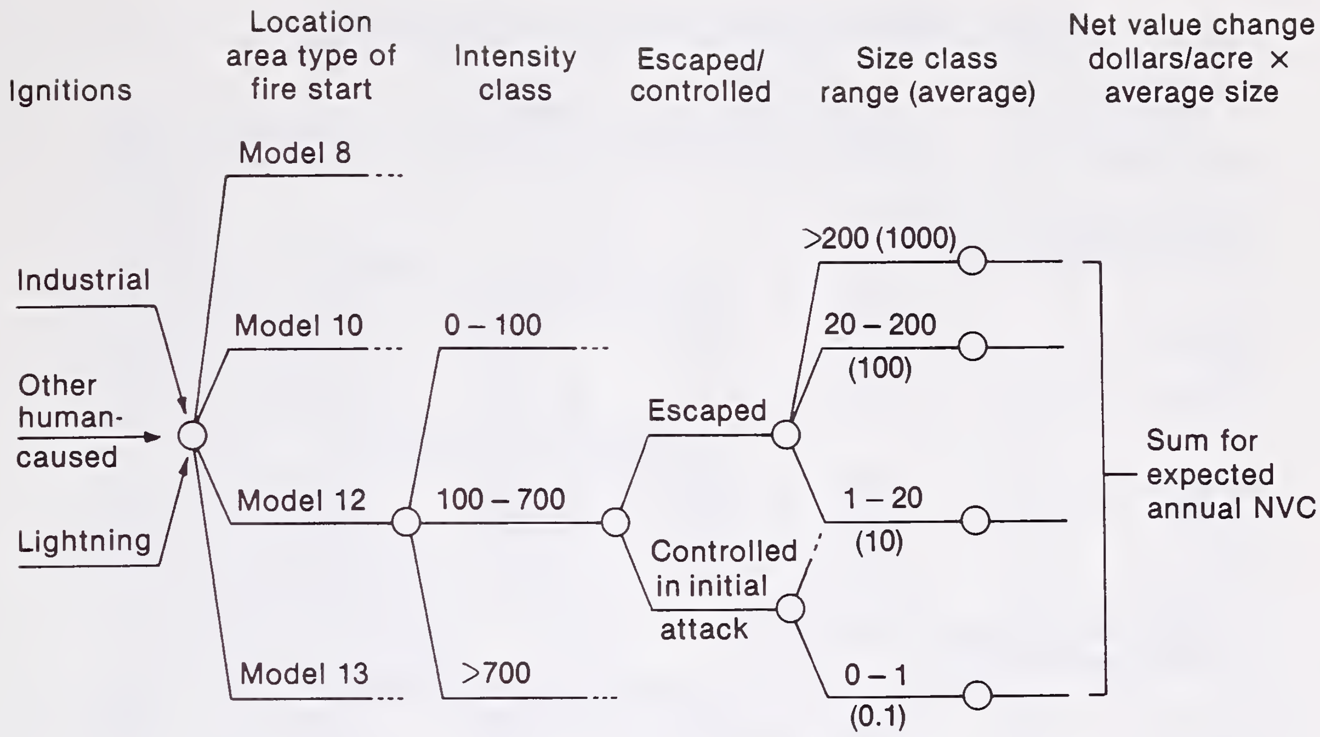


Figure 8.—Flow of cost-plus-NVC model.

Table 2a.—Base case results: Summary

Item	Area type at fire origin (fuel model) Heavy slash (13)	Medium slash (12)	Timber litter (8)	Litter + understory (10)	Total
Average number of fires per year by size class:					
0.1 acres	0.54	0.97	6.27	19.92	27.70
10 acres	1.33	0.98	0.33	2.80	5.44
100 acres	0.26	0.19	0.00	0.35	0.79
1,000 acres	0.03	0.02	0.00	0.02	0.07
Total	2.15	2.15	6.60	23.10	34.00
Average number of fires per year by intensity class:					
Low	0.00	0.06	6.60	18.02	24.68
Moderate	0.60	1.31	0.00	4.39	6.30
High	1.55	0.77	0.00	0.69	3.01
Total	2.15	2.15	6.60	23.10	34.00
Expected NVC ($1,000/year) by intensity class:					
Low	0.00	0.01	0.79	2.14	2.94
Moderate	6.31	13.55	0.00	74.67	94.52
High	64.84	32.42	0.00	52.13	149.39
Total	71.15	45.98	0.79	128.94	246.85
Total suppression cost ($1,000/year)			= 100.4		
Budget (including fuel treatment, $1,000/year)			= 743.0		
Total cost + NVC ($1,000/year)			= 1090.0		

the budget effectiveness), as was done in studies by Schweitzer et al. (1982) and U.S. Department of Agriculture, Forest Service (1980a). Rather, we chose to analyze several parameters of the budget decision, exploring a range of assumptions about budget effectiveness. Formulating the problem in this manner, we did not use the standard practice of directly testing the sensitivity of the decision to uncertainty in important variables. Instead, the method used involved carrying out extensive tests of the sensitivity of the outcomes (primarily resource value changes and associated suppression costs) to variations in input values and

Table 2b.—Base case results: Details (by intensity and size class)

Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres	Total
Area type: Heavy slash (model 13)					
Number of ignitions: 2.15					
		Number of fires (*average/year*)			
Low	0.00	0.00	0.00	0.00	0.00
Moderate	0.36	0.21	0.03	0.00	0.60
High	0.19	1.11	0.22	0.03	1.55
Total	0.54	1.33	0.25	0.03	2.15
		Net value change (*$1,000/year*)			
Low	0.00	0.00	0.00	0.00	0.00
Moderate	0.02	1.05	3.43	1.81	6.31
High	0.01	8.36	26.75	29.72	64.84
Total	0.03	9.41	30.18	31.53	71.15
Area type: Medium slash (model 12)					
Number of ignitions: 2.15					
		Number of fires (*average/year*)			
Low	0.06	0.00	0.00	0.00	0.06
Moderate	0.81	0.42	0.07	0.00	1.30
High	0.09	0.56	0.12	0.02	0.79
Total	0.96	0.98	0.19	0.02	2.15
		Net value change (*$1,000/year*)			
Low	0.00	0.00	0.00	0.00	0.01
Moderate	0.04	2.10	7.48	3.93	13.55
High	0.00	4.18	13.37	14.86	32.42
Total	0.05	6.28	20.85	18.80	45.98
Area type: Timber litter (model 8)					
Number of ignitions: 6.6					
		Number of fires (*average/year*)			
Low	6.27	0.33	0.00	0.00	6.60
Moderate	0.00	0.00	0.00	0.00	0.00
High	0.00	0.00	0.00	0.00	0.00
Total	6.27	0.33	0.00	0.00	6.60
		Net value change (*$1,000/year*)			
Low	0.13	0.66	0.00	0.00	0.79
Moderate	0.00	0.00	0.00	0.00	0.00
High	0.00	0.00	0.00	0.00	0.00
Total	0.13	0.66	0.00	0.00	0.79
Area type: Timber litter + understory (model 10)					
Number of ignitions: 23.1					
		Number of fires (*average/year*)			
Low	17.12	0.90	0.00	0.00	18.02
Moderate	2.72	1.40	0.25	0.01	4.39
High	0.08	0.50	0.10	0.01	0.69
Total	19.92	2.80	0.35	0.02	23.10
		Net value change (*$1,000/year*)			
Low	0.34	1.80	0.00	0.00	2.14
Moderate	0.27	21.07	37.53	15.80	74.67
High	0.01	9.98	19.96	22.18	52.13
Total	0.63	32.85	57.48	37.98	128.94

assumptions. The sensitivity information was then used as a basis for understanding, in a qualitative sense, the sensitivity of the budget decision to the inputs and assumptions.

A representative set of sensitivity tests is listed in table 3. Data used in the sensitivity tests are listed at the end of the appendix.

Critical Uncertainties

The sensitivity analysis showed that the fire loss estimates are quite sensitive to variations in the distribution of area (or fuel) types and to changes in fire intensity given the fuel type. As listed in table 3, doubling the assessed area represented by slash styl-

Table 3.—Sensitivity analysis (thousands of dollars per year)

Sensitivity case	Expected NVC	Expected suppression costs	NVC + suppression costs: differences from base case	
Base case	247	100	---	
Ignitions				
Subtract one industrial ignition	220	88	−39	(−11%)
Subtract one other human-caused ignition	240	98	−9	(−3%)
Slash area				
50% less slash area	202	80	−65	(−19%)
100% more slash area	369	164	+186	(+54%)
Fire intensity				
2 × fire intensities	560	191	+404	(+116%)
1/2 × fire intensities	200	84	−63	(−18%)
Number of escaped fires				
10% more escaped fires	268	109	+30	(+9%)
25% more escaped fires	301	121	+75	(+22%)
10% fewer escaped fires	225	92	−30	(−9%)
25% fewer escaped fires	193	80	−74	(−21%)
Values				
2 × NVC figures	494	100	+247	(+71%)
1/2 × NVC figures	123	100	−124	(−36%)

ized fuel models results in a 54% increase in the expected losses. This change occurs even though only 10% of the total area has been changed from the nonslash to the slash fuel types. Similarly, doubling the fire intensities more than doubles expected fire losses. A greater percentage of areas with high fuel loadings will lead to more fires having higher intensities. As was noted in the discussion of the base case results, these are the fires that produce the greatest resource impacts. An analogous effect is clear if all fires have higher intensities.

The great sensitivity of the outcomes to changes in the distribution of area types and fire intensities suggests that the budget decisions will also be sensitive to such uncertainties. For example, if one assumes that greater budget expenditure results in improved control effectiveness, such an increased budget is preferable given a greater percentage of area with high fuel loadings. On the other hand, lower fire intensities, less area with high fuel loadings, or a combination of the two may allow one to reduce the budget and realize a net reduction in cost plus NVC. (The fire intensity and area distribution uncertainties are modeled explicitly in the subsection Value of Information Analysis. The economic value of obtaining more information to reduce the uncertainties is discussed at that point.)

The outcomes of the annual budget request decisions are also sensitive to the annual number of ignitions. The optimal alternative varies symmetrically with the number of ignitions: More ignitions suggest a higher budget, and vice versa. This sensitivity was not as great as that found for area distribution and intensity, and few information-gathering options are available to reduce uncertainty in the number of future ignitions. This does not imply that expenditures on prevention activities will not reduce the number of ignitions; that is an action that changes the system rather than an information gathering activity. Thus it was deemed appropriate to evaluate the budget decision and value of information on the basis of the expected annual number of ignitions.

Although many fire management decisions are highly sensitive to daily fluctuations in weather, the budget-level decision is necessarily based on long-term climatological patterns. These patterns are generally well represented in the historical record. As a result, the decision is relatively insensitive to the low degree of uncertainty in the local long-term weather distribution. Spatial weather variations are important for detailed pre-attack planning, but they do not appear to significantly affect the overall annual budget decision when fire weather stations are properly located.

The effectiveness of various fire management and fuels treatment expenditures—that is, the effectiveness of the fire budget—is of considerable importance. It is also poorly understood. In formal terms, there is a wide range of uncertainty in the effectiveness of control resulting from a given budget level. In the present analysis, this uncertainty was investigated in two ways: The value of information on other parameters was calculated for a range of assumptions regarding budget effectiveness, and a simplified value of information calculation was carried out for the uncertainty in effectiveness itself.

The changes in resource value that result from fires of various intensities and sizes are subject to much debate. While timber values are reasonably well-known, the change in such values caused by fires (of varying intensity and extent) is uncertain. Other resource values, such as watershed or wildlife, rarely have explicit quantitative value assignments. Rather than interpreting this as an uncertainty that might be reduced with further information, we chose to evaluate the decision and the value of information over a wide range of possible fire damage costs or losses. The sensitivity of such values to variations in the losses is then evident.

We have not included an explicit test of sensitivity to the fire size distributions (i.e., to the distribution of fire sizes given area type, intensity, and escape status). The outcomes will clearly be sensitive to the probabilities of large fires. The distributions used (as listed in the appendix) reflect the best judgment of several Mount Hood National Forest fuels and fire managers and are also consistent with historical data. We have chosen to hold these distributions fixed, as a modeling assumption, to reduce the degrees of freedom in the model.

Insights from Sensitivity Analysis

The importance of sensitivity analysis goes beyond its role in identifying critical uncertainties. It can provide insights to help in understanding the system itself as well as decisions concerning its management.

Because of the uncertainty in budget effectiveness, it is not possible to provide a detailed analysis of the allocation of the overall fire management budget to particular budget categories. The sensitivity analyses do give, however, some feel for this issue. For example, the annual expected values of eliminating one industrial ignition or one other-human-caused ignition are, respectively, about \$39,000 and \$9,000. The costs of having an additional ignition in either category are similar. These values compare to a current prevention budget of about \$58,000 for the Clackamas and Estacada districts. If the prevention budget effectiveness is such that the number of nonindustrial ignitions can be expected to be reduced by one for an additional expenditure of less than \$9,000, such a budget allocation is worth considering. On the other hand, if reducing the prevention budget by an amount greater than \$9,000 led to an increase in the expected number of ignitions by less than one, then such an alternative should be pursued.

The effectiveness of fuel treatment activities in reducing wildfire losses is subject to much controversy. While the scope of analysis precludes detailed investigation of this issue, the sensitivity analysis may provide some insight. If the amount of area having a fuel load best represented by the slash stylized fuel models could be reduced by 50%, the action would have an expected annual benefit on the order of \$65,000. Recall that this is for the Clackamas and Estacada districts only. The value would be greater for the entire Mount Hood National Forest. Furthermore, it involves only fire-related savings. Direct benefits of slash treatment to resource values (e.g., enhanced esthetic values, better regeneration success, etc.) are not included.

This expected savings would accrue over each year that the slash area was maintained at a level of 50% below the present level. Comparing the costs of such treatment activities with this value will give some feel as to whether the present fuels treatment budget of \$477,000 is appropriate as a fire management expenditure.

Holding all other factors constant (in particular, area distribution and fire intensities), the value of reducing the number of escaped fires by 10% is about \$30,000 per year. The added cost of allowing 10% more fires to escape initial attack is similar. If increasing the presuppresion budget by an amount less than \$30,000 can achieve a 10% reduction in escapes, such a budget increase would be desirable. Conversely, if more than \$30,000 can be saved from the budget by allowing 10% more fires to escape, this alternative should be seriously considered.

Value of Information Analysis

Three different value-of-information analyses were carried out for the fire management budget request decision. The value of reducing uncertainty in the assignment of forest area to the available stylized fuel models and in predicting fire intensity given fuel type was investigated in some detail. Brief discussions of the value of information on budget effectiveness and the value of adding an additional stylized fuel model to the available set follow.

Value of Information: Fuels and Fire Intensity

Before examining the value of information in detail, it is necessary to define more fully the decision being analyzed. In general terms, the alternatives are to request an increase in the fire management budget, to request the present budget level, or to request a lower budget. Several different amounts of potential budget increase or decrease were investigated. The uncertainties considered explicitly are the assignment of stylized fuel models to the total area (area distribution) and the fire intensity given fuel type and weather characteristics (intensity). The outcomes are expected values for total budget, net resource value changes, and suppression costs. The decision criterion is to minimize expected costs plus NVC. Other than for budget alternatives, area distribution, and fire intensity, all data used reflect the base case discussed earlier in this section. (Data for the base case are summarized in the appendix.)

To provide an internally consistent framework for evaluation, a parametric approach was used to model the change in fire control effectiveness given changes in budget. It was assumed that changes in fire management budget change the probability of controlling a fire with intial attack forces. This could occur through changes in presuppression, fuels treatment, or initial attack activities. Changing the probability of achieving control during initial attack implies a change in the number of escaped fires—the dominant category in fire losses. Two cases were examined, one in which increasing or decreasing the fire budget by some arbitrary amount causes a 10% increase or decrease in the number of escaped fires and one in which a budget change results in a 50% increase or decrease in escapes. The magnitude of budget change needed for these effectiveness changes was varied, providing a range for the value of information calculations.

Note that we are examining decisions involving incremental changes in the budget level. Similar incremental decisions at different base budget levels will result in different information values, but likely on the same order of magnitude as those found in this case study.

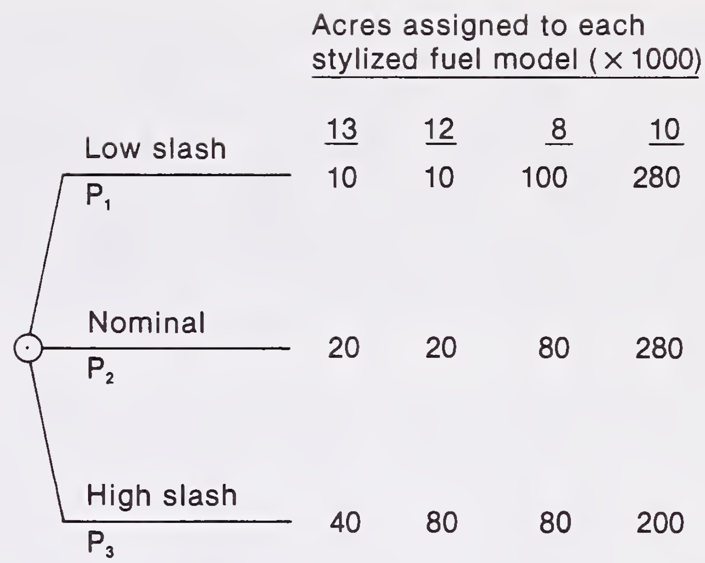
Area Distribution Uncertainty.—Uncertainty in the assignment of stylized fuel models to the Clackamas and Estacada districts is represented in figure 9. The range of possible assignments was approximated by a discrete probability distribution over the three breakdowns: a nominal (or most likely) distribution, a low-slash case, and a high-slash case. Five fire management specialists from the Mount Hood National Forest participated in the encoding session at which this distribution was defined. Figure 9 represents their consensus view. The probabilities used (0.3, 0.4, 0.3) reflect a discrete approximation of the continuous distribution implied by the consensus that the probability is low that the amount of slash will exceed the high-slash case or fall below the low-slash case. The reduced uncertainty case can be given two alternative interpretations: (1) For a national forest such as the Mount Hood, it represents the uncertainty remaining after more (but still imperfect) information is made available, or (2) it represents the initial uncertainty for a forest having better information on fuel conditions at the outset.

Fire Intensity Uncertainty.—The uncertainty in fire intensity, given an accurate choice of fuel models, is represented in figure 10. As noted previously, the nominal intensities are those calculated directly by the Rothermel (1972) fire behavior model. Actual fireline intensities can be expected to fall within the range of one-half of the nominal model-generated fire intensity up to twice the nominal intensity output (Albini 1976). This uncertainty in fireline intensity is approximated by the nominal probability distribution listed in figure 10 for the half-nominal, nominal, and two-times-nominal intensities.

Each of the three cases forming the branches of the probability node in figure 10 is actually a set of four distributions (with weather variations factored in) on fireline intensity—one for each fuel model. The discrete versions of these distributions are shown in the appendix. The nominal case is included with the base case data, and the half- and double-intensity cases are found with the sensitivity analysis data.

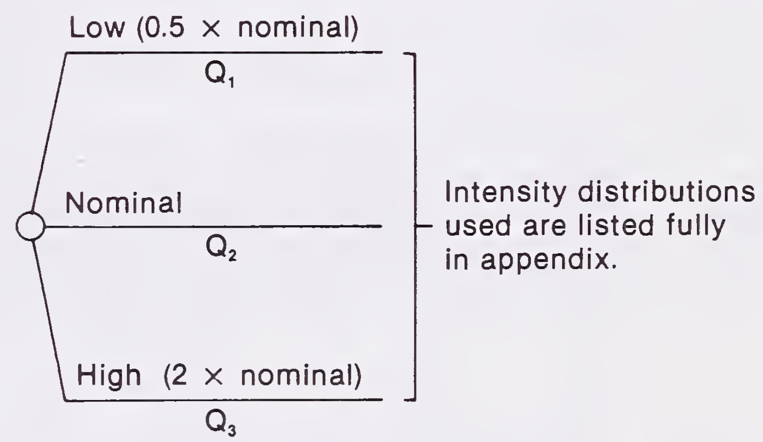
Decision Tree.—The complete decision tree used for the analysis of the value of information on area distribution among fuel models and on fire intensity is shown in figure 11. Outcome values (total cost plus NVC—excluding fuel treatment and brush disposal costs) are listed for two decision situations, for which the alternatives of raising or lowering the fire budget result in either a 10% change or a 50% change in the number of fires escaping initial attack. The budget increments necessary to produce these changes in effectiveness—that is, the budget changes implied by the increase or decrease alternatives—are denoted as Δ_1 and Δ_2. The uncertainties in the distribution of fuel model types and in fire intensities are shown explicitly. Probabilities for the area distribution uncertainty are shown in figure 9. Probabilities describing the uncertainty in intensity are listed in figure 10.

Analysis.—Cases representing a wide range of situations were evaluated. The optimal decision alternative and expected cost plus NVC given the initial uncertainty, the value of perfect information on the area distribution, and the value of perfect information on fire intensity were determined for each case. The deci-



Probability distributions	P_1	P_2	P_3
Nominal uncertainty	0.3	0.4	0.3
Reduced uncertainty	0.1	0.8	0.1

Figure 9.—Area distribution uncertainty.



Probability distributions	Q_1	Q_2	Q_3
Nominal uncertainty	0.3	0.4	0.3
Reduced uncertainty	0.1	0.8	0.1

Figure 10.—Fire intensity uncertainty.

sion tree shown in figure 11 provided the framework for these computations. Varied over the cases are the effect of the budget increase or decrease alternatives (+/− 10% or +/− 50%), the cost of effecting these changes (Δ_1 and Δ_2), and the initial uncertainty in area distribution and fire intensity (see figures 9 and 10). A summary of some of the most interesting cases is provided in table 4. A complete list of cases can be found in table 5. Information values are given in dollars per acre per year.

For decisions involving relatively small changes in the budget level (on the order of 10-20%), the value of obtaining perfect information on the distribution of fuel types was very small, typically less than one cent per acre per year (e.g., scenarios 1 through 5 in table 4). Most annual decisions regarding budget level will involve alternatives of this magnitude, which corresponds to an information value of roughly $10,000 per year for the Mount Hood National Forest. Recall that this is the value of perfect information. Most information-gathering alternatives will still leave one short of certainty. For the decisions involving incremental changes in budget, the value of perfect information on fire intensity was generally in the range of one to three cents per acre per year, which corresponds to $10,000 to $30,000 per year for the Mount Hood National Forest. Representative cases are found in table 4.

When decisions involving greater changes in resource allocations are considered, it is reasonable to expect that the value of reducing uncertainty will be greater. The analysis results confirm this supposition. When a major decision is contemplated, such as raising or lowering the budget by about 50% of the present level, the value of reducing uncertainty increased significantly. The expected value of perfect information on the distribution of area types, in the context of such major decisions, ranged from zero to seven cents per acre per year. The value of fire intensity information, on the other hand, was as high as 19 cents per acre per year. Most values were less than 10 cents per acre per year (see scenarios 6 and 7 in table 4). For the Mount Hood National Forest, one cent per acre corresponds roughly to $10,000.

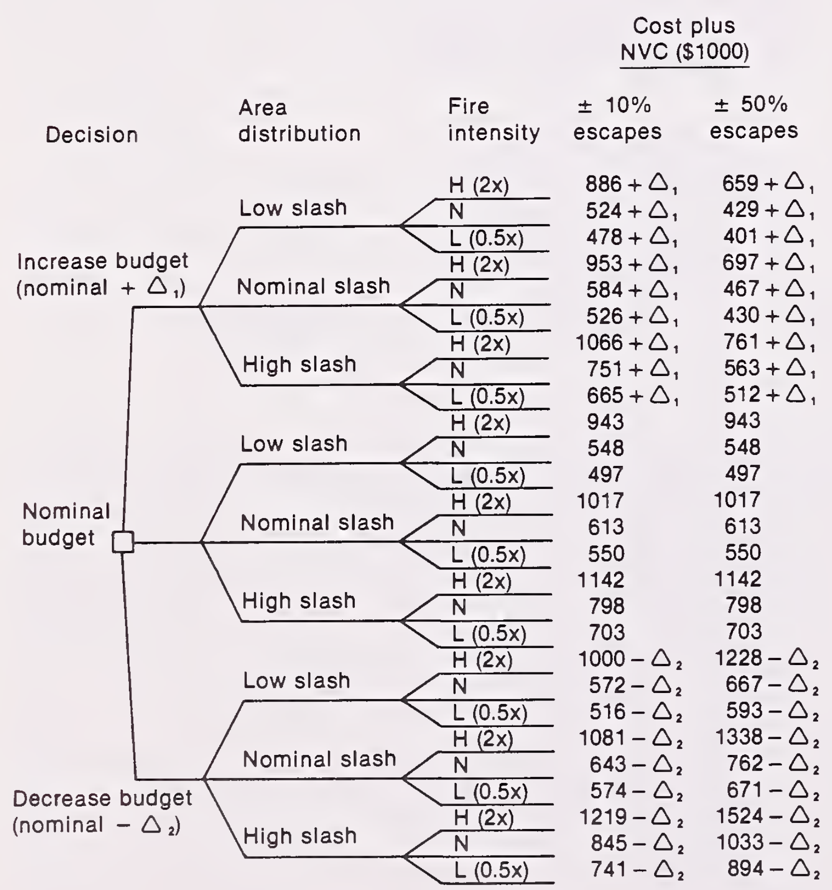


Figure 11.—Budget analysis decision tree.

Some general patterns are apparent in the range of situations analyzed. The value of reducing uncertainty about fire intensity, given a proper fuel model, was virtually always greater than that for reducing uncertainty in the area distribution of fuel models. Many situations in which more information on the distribution of fuels would not change the budget decision—and, thus, would have no economic value—still showed a positive EVPI for fire intensity.

For either uncertain parameter, changing the initial probability distribution from the nominal to the reduced uncertainty case resulted in a reduction in the EVPI of 50-75%. One might conclude that the value of new information that would allow this degree of reduction in uncertainty is about one-half of the nominal EVPI. This implies that the value of such imperfect information on the distribution of fuel types for the Mount Hood National Forest is no more that $5,000 per year in the context of annual incremental budget decisions. The value of improved but imperfect information on fire intensity would be about $10,000 annually. These values would be about three times larger if decisions regarding major portions of the budget (e.g., 50%) were faced.

An interesting pattern found for decisions involving relatively small fractions of the existing budget was that reducing the initial uncertainty in fire intensity often induced an increase in the EVPI on the fuel model area distribution. This suggests that a synergism may exist. Investing resources in developing an improved fire behavior model (and thus reducing uncertainty in intensity given the fuel distribution) can actually increase the value of gathering more information on fuel properties and distributions. Results of ongoing research to improve fire behavior prediction capabilities may eventually justify expenditures larger than one or two cents per acre per year for better fuel information.

Situations in which the effectiveness/budget relationship was assumed to be linear about the nominal budget level (equivalently, constant returns to scale) generally had lower information values than were found for cases in which the budget increase required for improved effectiveness was significantly different from that saved in return for accepting less effectiveness. For example, scenario 1 in table 4 is a case in which a 10% increase or decrease in budget results in the same (+/− 10%) change in effectiveness (the number of escaped fires). This decision scenario has zero EVPI values for information on both fuel distribu-

Table 4.—Value of information cases: Summary

Decision scenario	Best alternative under uncertainty	Expected cost + NVC	Expected value of perfect information: On area distribution	Expected value of perfect information: On fire intensity
		$1,000/year	*dollars per acre per year*	
1. Alternatives include nominal and +/−10% of presuppression, prevention and initial attack budget to produce +/−10% in escapes	Increase budget	729	0.00	0.00
2. Same as 1, except with reduced initial uncertainty on intensity	Increase budget	671	0.00	0.00
3. Alternatives include +/−15% of budget to produce +/−10% escapes	Increase budget	742	0.01	0.03
4. Same as 3, except with reduced initial uncertainty on both area and intensity	Decrease budget	652	0.005	0.01
5. Alternatives include +10%/−20% of budget to produce +/−10% escapes	Increase budget	729	0.01	0.03
6. Alternatives include +/−60% of budget to produce +/−50% in escapes	Increase budget	698	0.00	0.04
7. Alternatives include +75%/−50% of budget to produce +/−50% escapes	Increase budget	738	0.04	0.08

Table 5.—Value of information results

Δ_1	Δ_2	Area distribution uncertainty[1]	Fire intensity uncertainty[1]	Best alternative under uncertainty[1]	Expected value	EVPI: On fuel load and location	EVPI: On fire intensity
percent of budget					*$1,000/year*	*dollars per acre per year*	
			Scenarios involving +/−10% of escaped fires				
10	[2]10	N	N	+	729	0.00	0.00
10	[3]10	N	R	+	671	0.00	0.00
10	10	R	N	+	712	0.00	0.003
10	10	R	R	+	652	0.00	0.001
15	[4]15	N	N	+	742	0.01	0.03
15	[5]15	R	R	−	652	0.005	0.01
10	15	N	N	+	729	0.001	0.01
15	10	N	N	+	742	0.008	0.02
10	[6]20	N	N	+	729	0.01	0.03
20	10	N	N	N	737	0.00	0.009
5	10	N	N	+	716	0.00	0.00
10	5	N	N	+	729	0.00	0.00
			Scenarios involving +/−50% of escaped fires				
50	50	N	N	+	672	0.00	0.00
60	[7]60	N	N	+	698	0.00	0.04
40	40	N	N	+	645	0.00	0.00
75	75	N	N	+	738	0.07	0.17
75	75	N	R	−	660	0.02	0.06
75	75	R	N	−	722	0.03	0.19
75	75	R	R	−	627	0.02	0.06
60	30	N	N	+	698	0.00	0.02
30	60	N	N	+	618	0.00	0.00
75	[8]50	N	N	+	738	0.04	0.08
75	50	N	R	N	679	0.03	0.03
50	75	N	N	+	672	0.007	0.05
50	25	N	N	+	672	0.00	0.00
25	50	N	N	+	605	0.00	0.00

[1]*N = Nominal*
R = Reduced
+ = Increase
− = Decrease

[2]*Scenario 1 in table 4.*
[3]*Scenario 2 in table 4.*
[4]*Scenario 3 in table 4.*
[5]*Scenario 4 in table 4.*
[6]*Scenario 5 in table 4.*
[7]*Scenario 6 in table 4.*
[8]*Scenario 7 in table 4.*

tion and on fire intensity. In contrast, in scenario 5, the budget could be cut by 20% at the cost of accepting 10% more escapes, while decreasing the number of escapes by 10% requires only a 10% increase in the budget. This case has considerably greater EVPI results: \$0.01/acre/year for fuels information and \$0.03/acre/year for fire intensity information. This general pattern is reasonable: The nonlinear scenarios imply greater sensitivity to surprises or unlikely outcomes. Thus, the value of eliminating uncertainty in such cases is likely to be greater.

Value of Adding a Fuel Model

Part of the uncertainty in the assignment of acreage within the Clackamas and Estacada districts to stylized fuel model types can be attributed to the small number of fuel models from which one must choose. It is reasonable to wonder whether a finer grained set of fuel models would eliminate or reduce uncertainty.

A decision problem was set up in which it was assumed as an extreme case that all uncertainty in the area distribution was caused by an insufficiently detailed set of stylized fuel models and that all such uncertainty could be removed by the addition of one more model. This structure should provide an upper bound on the value of adding another fuel model to the existing set in the context of fire management budget decisions.

Forest personnel seemed to have greatest difficulty assigning an appropriate fuel model to areas where slash had been overgrown by brush. A new fuel model was constructed to specifically represent this situation. Its fire behavior characteristics were intermediate to those of models 12 and 13.

The upper decision tree in figure 12 describes the decision situation when only the existing set of fuel models is available. The uncertainty as to how the area should be assigned to the available stylized models is shown explicitly. The lower tree in the figure represents the situation when the new stylized model is available; no uncertainty remains (again, note that this is purposely an extreme case). The decision alternatives are again whether to increase the fire management budget, leave it at the current level, or decrease the budget. The effectiveness of increasing or decreasing the budget was modeled by a 10% increase or decrease in the number of escaped fires. The uncertainty in budget effectiveness was explored by varying Δ_1 and Δ_2 over a wide range to ascertain the sensitivity to these parameters.

The results of this analysis were rather clear: Creating an additional stylized fuel model (and thus removing a source of uncertainty) generally did not result in a change in the preferred alternative. In such cases, since the additional model failed to change the decision, its availability had no value. Only a few instances (settings of Δ_1 and Δ_2) were found in which a different alternative was shown to be optimal when the fifth fuel model was added. Such cases, however, were those in which the alternatives resulted in outcomes

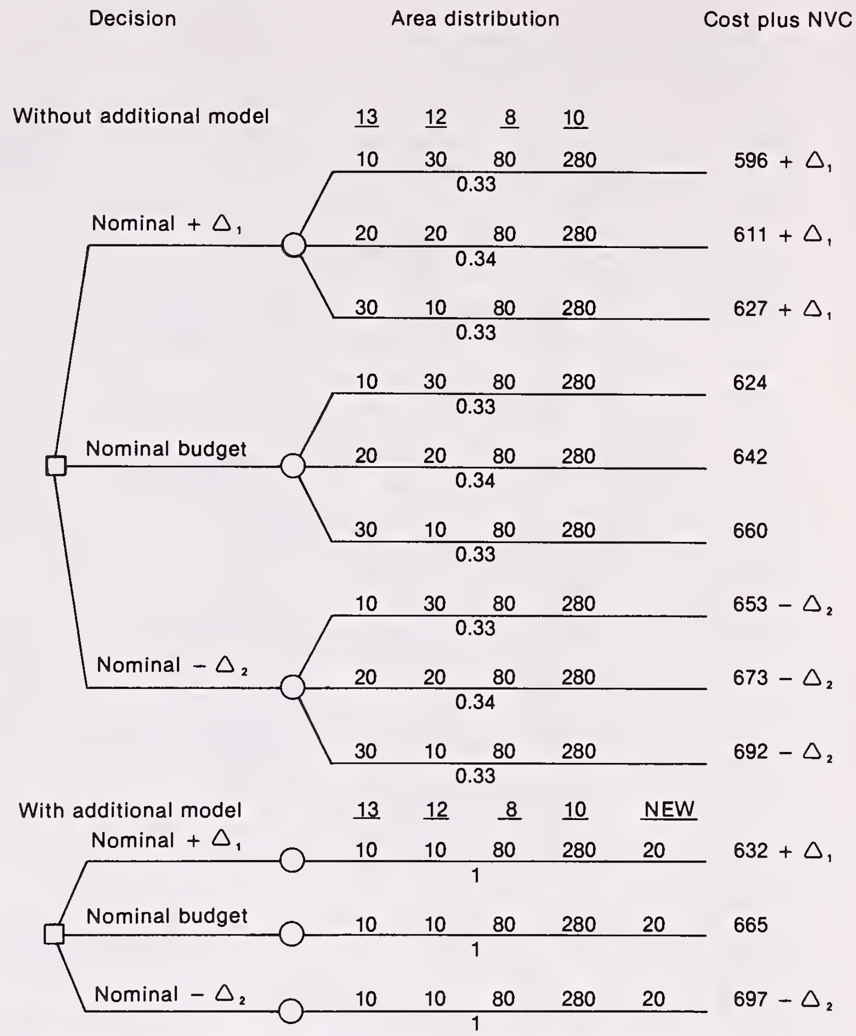


Figure 12.—Decision trees without and with an additional stylized fuel model.

that were so close that the cost of a "wrong" decision was insignificant. For example, in a case where both Δ_1 and Δ_2 were assumed to be \$32,000 (about 12% of the nominal budget), the decision when limited to four stylized models was to maintain the nominal budget level. When the new fuel model was added, the budget increase alternative was preferred. By examining the alternative from the first four-model case (nominal budget) in the five-model decision structure, we find an increase in cost plus NVC of only \$1,000, or approximately one-tenth of 1%. These results are insensitive to variations of 50-200% in the area allocated to the hypothetical new stylized fuel model.

We would conclude that for the purposes of the budget-level decision in areas such as the Mount Hood National Forest, the existing set of 13 stylized fuel models (Albini 1976) provides sufficient resolution. A more detailed set of models may be of value for other decision contexts.

Value of Information: Budget Effectiveness

It has been noted several times that the effectiveness of the fire management budget is uncertain. It is not well understood how great a change in effectiveness (and, ultimately, fire costs and resource value changes) will result from a given change in the fire management budget. In the analyses presented earlier, the implications of this uncertainty were examined by calculating information values for a range of effectiveness

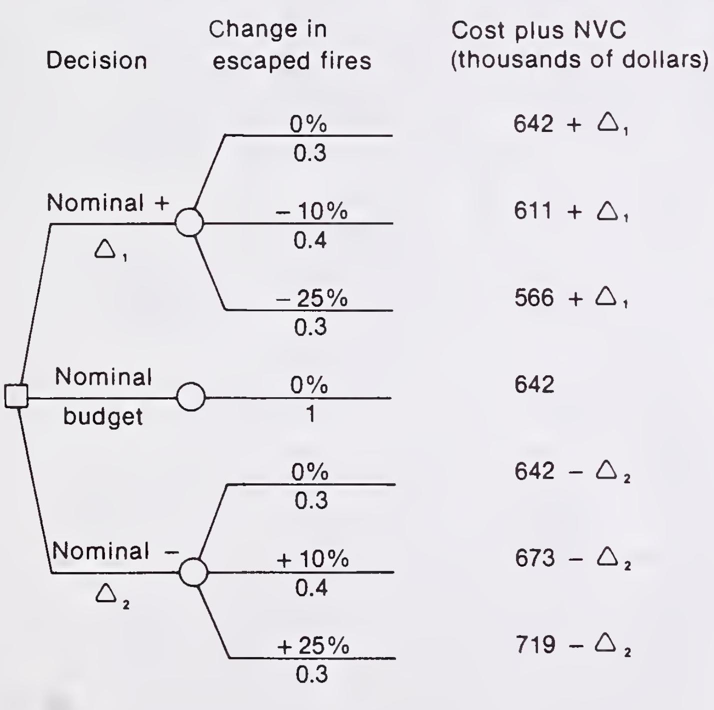
change/budget change scenarios. At this point, we will examine the uncertainty explicitly with a simplified decision problem.

The decision tree for this analysis is shown in figure 13. Uncertainty in area distribution and fire intensity is suppressed. It was assumed that it was uncertain what change in the number of escaped fires would result from a given change in budget. The three points modeled in the tree are no change, 10% change, and 25% change. Again, several budget change levels were examined to produce a range for the expected value of perfect information. Typical values were about five cents per acre per year, or about $50,000 annually for the Mount Hood National Forest. It should be reiterated that this is the value of perfect information and thus an upper bound on the cost of any information-gathering efforts to resolve uncertainty in the relationship between the presuppression budget and initial attack effectiveness.

Information Alternatives

Fuel Loading/Distribution of Fuel Types

The EVPI on the distribution of area types was on the order of $10,000 per year for the Mount Hood National Forest. This is clearly not enough to support any significant ground-level, information-gathering activity, although future changes in ignition risk, resource values, and levels of other uncertainties could someday make these intensive activities worthwhile. For now,



Budget change (percent of nominal) Δ_1	Δ_2	EVPI (dollar • acre $^{-1}$ • year $^{-1}$)
10%	10%	$0.04
15%	15%	0.05
20%	20%	0.04
10%	15%	0.06

Figure 13.—Decision tree for evaluating EVPI on budget effectiveness.

expenditures only up to one or two cents per acre per year on efforts to improve the classification of the forest by fuel model may be justified. Periodic examination by air of slash/brush conditions in old cut-blocks or use of an improved system of record-keeping to better utilize information already available (e.g., from timber cruises, timber sale records, fuels treatment activities, and other resource management functions) could probably be accomplished at this cost. Note that for fire management budget analysis purposes, the spatial pattern of fuel types is less important than the aggregate amount of area best represented by each type. The fire budget decision is sensitive to the overall fire hazard level but not to the detailed pattern of fire activity.

Funds invested in developing systems applicable to many national forests may be of greater value. For example, $3,000 per year per forest multiplied by 70 forests implies a research budget for aggregate fuels inventory systems of roughly one-quarter of a million dollars per year. Such a value would be appropriate only if results found for other national forests are of the same order of magnitude as those found in this case study.

Fire Behavior/Fire Intensity

Information useful in refining estimates of fire behavior would generally take two forms: improved understanding of the physical processes involved and improved models to explicitly represent these processes. Research in these areas would presumably be applicable over broad regions or over the entire country, as opposed to a single forest. This suggests that the cost of such research should be compared to the aggregate value of information over the country or the region involved.

The expected value of perfect information on fire behavior (specifically fireline intensity), given fuel load and weather conditions, was found for the Mount Hood National Forest to be on the order of $20,000 annually (assuming that the majority of budget decisions are of the incremental nature, as opposed to a major (i.e., +/– 50%) change). It is likely the research leading to improved models and experimental calibration of such models would reduce uncertainty but not eliminate it. Comparison of the EVPI for the reduced uncertainty case with that for the nominal case suggests that the annual value to the Mount Hood National Forest of such an improved capability would be in the range of $5,000 to $10,000 per year. Aggregating over a specific region or over the entire National Forest System would give an idea of the potential value of such research for the purpose of fire management budget formulation.

Fire Management Effectiveness

The uncertainty in the relationship between budget level and the effectiveness of initial attack is of a different nature from those uncertainties discussed previously and has to do as much with the performance of personnel as with physical processes. Reducing such

uncertainty would facilitate better decisionmaking regarding fire management expenditures. The upper bound on the value of such information for the Mount Hood National Forest is roughly $50,000 per year. Again, this is the expected value of perfect information. The resources that should be devoted to developing an improved understanding of budget effectiveness are likely to be considerably lower than $50,000 but can be significant when aggregated for the Forest Service as a whole.

FUEL TREATMENT DECISION

This section is a discussion of a site-specific decision: Which fuel treatment alternative is appropriate after a timber harvest operation? The structure and detail of the problem being analyzed are based on a specific harvest site on the Mount Hood National Forest. In addition, variations from the specific situation are examined to offer insight on a wider range of decisions of the same general type.

The Decision

The decision addressed in this section involves the choice of postharvest fuel treatment for a proposed 25-acre harvest. The site chosen for this analysis has characteristics that make the decision relatively complex (these characteristics are discussed later). Many fuel treatment decisions are much simpler in nature.

The Specific Site

The site under consideration consists of 25 acres of old-growth Douglas-fir with scattered white pine (*Pinus monticola* Dougl.) and hemlock (*Tsuga heterophylla* (Raf.) Sarg.) on the Clackamas District of the Mount Hood National Forest. Some understory growth is present, together with a significant quantity of timber litter. Preharvest loadings of fine woody fuels (less than 3 inches in diameter) are estimated to be on the order of 1-2 tons per acre. The area is at an elevation of 3,000 feet, with a southwest aspect. The slope is about 45%.

The proposed harvest area is to be clearcut, using a one-end suspended skyline system. All Douglas-fir and hemlock are to be cut; the white pine will be left as seed trees. An important characteristic of the site is its remoteness: Access is very poor.

In making the treatment decision, the fuel management staff faces several considerations:

1. A considerable, though uncertain, quantity of activity fuel (cutting slash) will be created during the harvest.
2. It is desirable to reduce the quantity of this fuel to create planting sites, reduce fire hazard, and improve wildlife habitat.
3. The poor access to the area makes treatment activities relatively expensive.
4. It is important to retain the duff/humus layer in order to protect site quality.
5. Damage to or destruction of a significant portion of the white pine stand will make hand planting necessary and greatly increase regeneration costs.

Alternatives Considered

Three alternatives under consideration by Mount Hood National Forest staff were evaluated, and further implications of some alternatives were investigated.

1. No Treatment.—The no-treatment alternative actually involves a very minimal treatment with spot treatment efforts by hand. The white pine would be retained, but planting sites would be of questionable quality, given the heavy load of activity fuels. The posttreatment fire hazard would be high. An important question involves the cumulative effects of selection of this alternative for a large number of sites. If the no-treatment alternative was selected for the majority of harvest sites, the amount of area in slash would increase. This would have implications on the overall level of fire hazard. The cost of the no-treatment alternative is very low—about $100 per acre.
2. Prescribed Burn.—The burn alternative involves a coarse (8×10) yarding of unmerchantable material (YUM) (removing all woody material greater than 8 inches in diameter and 10 feet in length) followed by broadcast burning. It has the advantage of providing a considerable reduction in fuel load at an intermediate cost. This must be balanced with the uncertainty in the outcome of the burn. A low-intensity burn may result in insufficient fuel reduction; or if the burn becomes too intense, it may result in damage to the white pine or the duff/humus layer. There is also the possibility of the fire's escaping prescription, with attendant costs and damages. The remote location of the site under consideration gives this alternative an estimated cost of $800 per acre.
3. Intensive.—The intensive treatment option involves YUM to a 6×6 standard. It has the advantage of greatly reducing risk to the white pine stands while providing significant reduction in fuel load. The cost is high—approximately $1,300 per acre. Because of the uncertainty in fuel load and site conditions, it is not possible to predict precisely the cost of achieving a given level of fuel load after treatment. This uncertainty can be modeled in a number of ways. We have chosen to represent it by assuming that the treatment cost is fixed, but that the amount of posttreatment fuel loading is uncertain and determined by the pretreatment load.

Decision Structure and Data

A sequence of decisions is involved in determining the form of fuel treatment for a specific site. These decisions range from the initial decision regarding the harvest to the final choices made by the crew carrying

out the prescribed treatment. Important uncertainties include the amount of preharvest (natural) fuels, the quantity of activity fuels created during the harvest, and the effects of the chosen treatment alternative. Timber values are reasonably well known, but the relationships among silvicultural technique, treatment method, and future timber production are complex and uncertain. Values related to other resource uses, such as watershed and wildlife, are poorly defined. In the analysis discussed later in this section, a wide range of sensitivity analyses and various decision scenarios were used to investigate the implications of different value assumptions and to provide insights into treatment decisions other than the specific case on the Mount Hood National Forest.

The complexity of the situation is illustrated in figure 14. Our discussion will emphasize the fuel treatment decision, and the analysis will focus principally on the postharvest treatment decision. In practice, the fuels management staff devotes considerable effort to the analysis of treatment alternatives before the harvest is carried out. The tentative choice of treatment is used to calibrate treatment costs during bidding for the harvest site by timber industry groups. The costs of a "wrong" decision (e.g., one that is changed after more information is available after the harvest) are due to the procedural details of the Forest Service/timber industry relationship. It is difficult to collect funds in excess of those originally estimated to be necessary, and there are incentives against refunds as well. Although the decision was complex, it was decided that the appropriate focus of this analysis was on the post- rather than the pre-harvest treatment decision. This way emphasis can be placed on the physical processes and systems rather than organizational and financial procedures and regulations.

The decision tree in figure 15 shows the postharvest treatment decision in greater detail. Implementing an analysis based on the structure of this decision required addressing several modeling and assessment issues.

Fuel Loading Uncertainty.—A critical uncertainty, both in analyzing the decision and determining the value of information, was in the quantity of fine fuels after harvest operations. Postharvest fine fuels (less than 3 inches) include both natural and activity fuels. The initial uncertainty in fuel load was assessed as follows. A Clackamas District fuels management specialist familiar with the site was shown a photo series representation of medium slash (Maxwell and Ward 1976) produced on a site similar to the one in question using a similar harvest technique. He was not allowed access to the published loading measurements accompanying the photograph. The visual information provided by the photo series was assumed to be representative of that provided by a postharvest inspection of the site. Standard interview techniques (Spetzler and Stael von Holstein 1975, Stael von Holstein 1970) were used to encode the subject's uncertainty about the actual quantity of fine fuels given that the chosen photograph accurately portrays on-site conditions. The resulting cumulative probability distribution is shown in figure 16.

The assessed distribution was approximated by a three-branch, discrete probability distribution (fig. 17), with probabilities of 0.25, 0.5, and 0.25, respectively, that the fuel loading is 8-14, 14-20, and over 20 tons per acre. This distribution was used in all subsequent analyses of the fuel treatment decision and provides the basis for calculation of the economic value of gathering more information on fuel load prior to making the postharvest treatment decision.

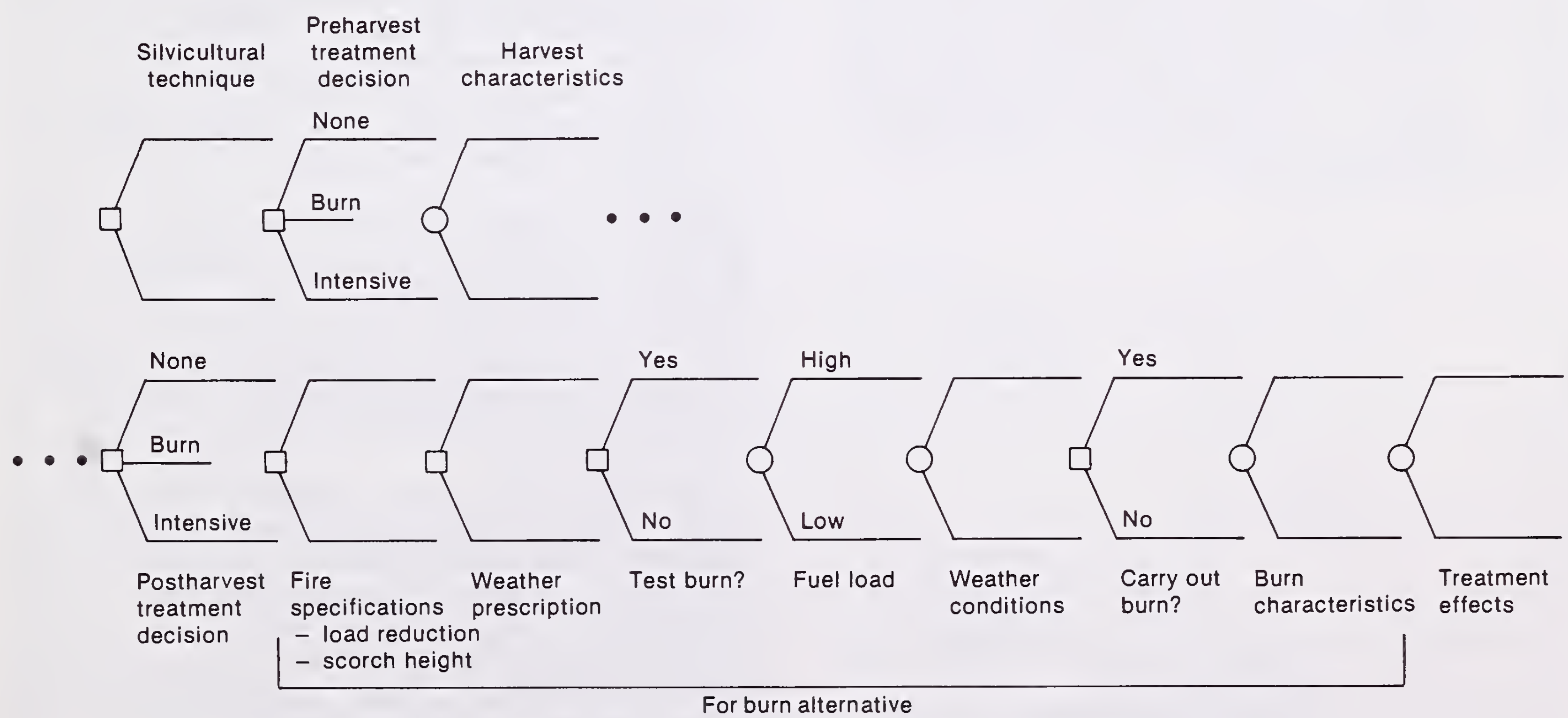


Figure 14.—Sequence of harvest and treatment decisions.

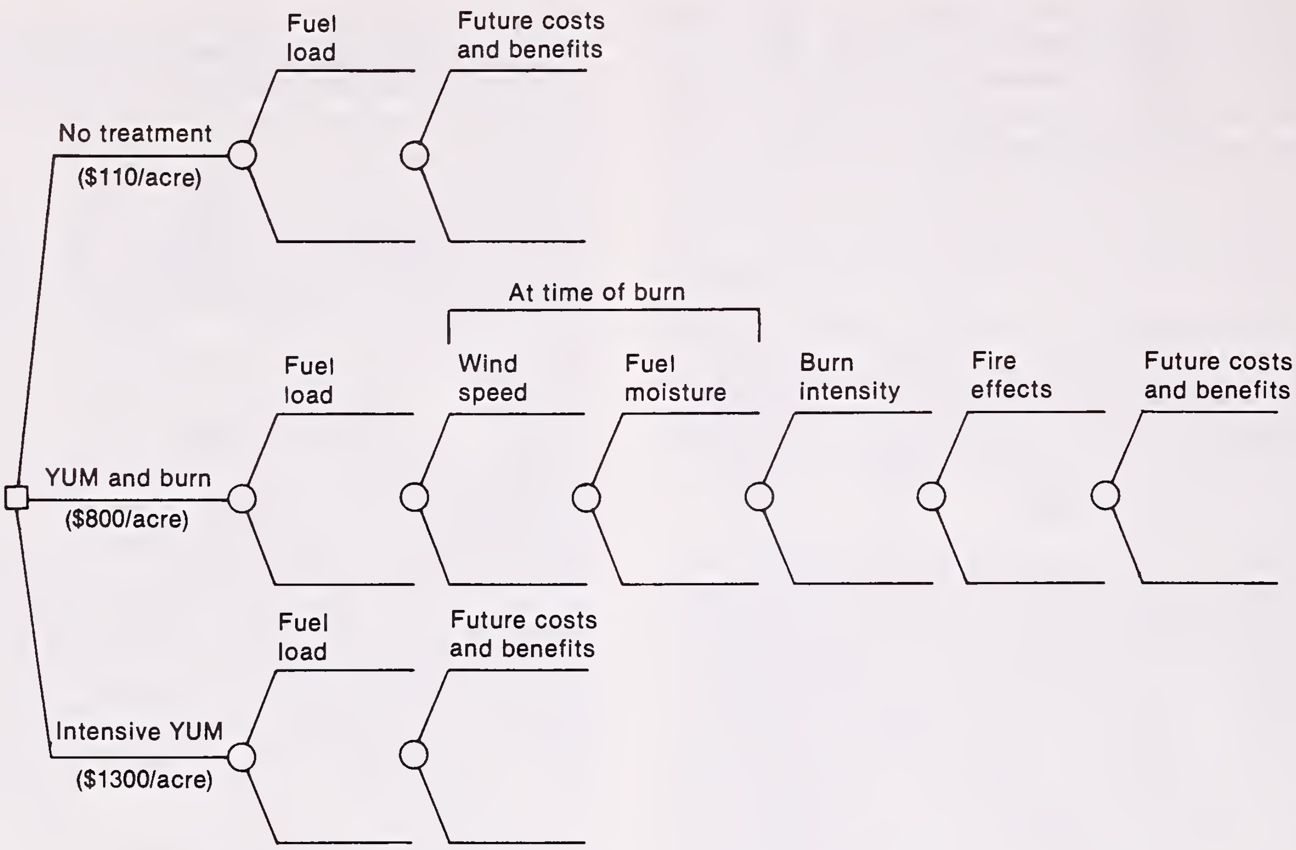


Figure 15.—Structure of postharvest fuel treatment decision.

Fire Intensity.—A second critical uncertainty for the prescribed burn alternative is the severity of the burn. Although a large number of fire characteristics interact in a complex manner with various site factors to determine the results of a fire, we have chosen to integrate many of these factors using predicted fireline intensity (Bryam 1959) as an index of potential burn severity. Several previous evaluations of fire management activities have also expressed potential fire effects as conditional on fireline intensity (Hirsch et al. 1979, Schweitzer et al. 1982, U.S. Department of Agriculture Forest Service 1980a). Modeling uncertainty in fireline intensity was carried out in three steps, the first two of which are described here and the third in the following subsection.

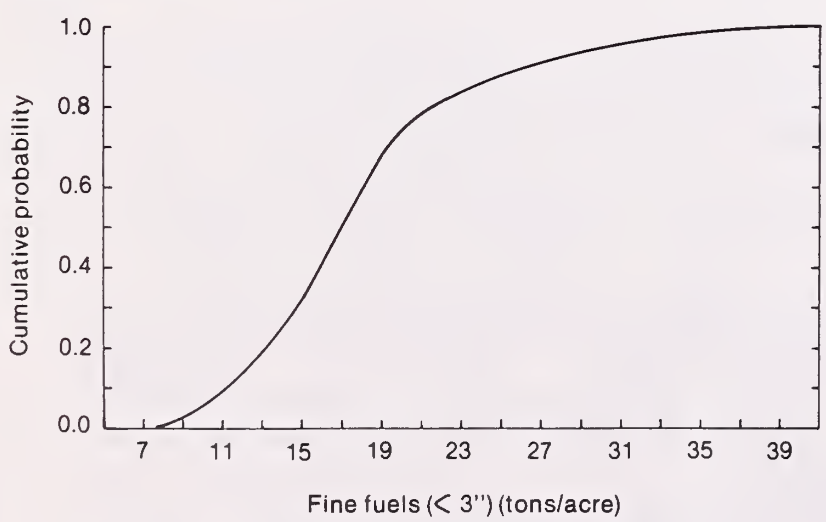


Figure 16.—Uncertainty in postharvest fuel load.

The three steps involve:

1. Explicitly characterizing the uncertainties in fuel moisture, wind speed, and fire behavior predictions.
2. Combining the three uncertainties with the predicted fire intensities (given as a function of fuel load, fuel moisture, and wind speed) to produce cumulative probability distributions describing fire intensity given the fuel load.
3. Combining the cumulative distributions on fire intensity with assessments of both acceptable intensity ranges and the ability of the burn crew to compensate for nonoptimal weather conditions to produce discrete probability distributions on the outcomes.

Predictions of fire intensity given wind speed and fuel moisture were provided by an existing fire behavior model (Rothermel 1972). An example of the output from this model is shown in figure 18 for the case with a fine fuel loading of 27 tons per acre. Uncertainty in the predicted intensity as a result of model and data approximations is represented in the top node of figure 19 (Albini 1976).

The weather prescription for a broadcast burn includes the range of acceptable wind speed and fuel moisture conditions. The actual conditions at the time of burn are, within this range, uncertain from the perspective of the individual making the treatment method decision. The bottom two nodes in figure 19 reflect the uncertainty likely to be present, based on the judgment of the Mount Hood National Forest fuels specialist.

Uncertainties in fire behavior predictions, fuel moisture, and wind speed were factored together with the fire behavior model output to produce cumulative probability distributions for intensity, given fuel loading. Each combination of fuel loading, model variation, wind speed, and fuel moisture resulted in an intensity figure and associated probability of occurrence. These intensities and probabilities were combined to produce the three distributions shown in figure 20, one for each separate fuel loading level. These distributions reflect all three uncertain factors (assumed to be mutually independent) shown in figure 19.

Compensation Capability and Acceptable Intensity Range.—The fire intensities just discussed leave out one important factor: the ability of firing crews to compensate for existing wind and fuel moisture conditions by varying the ignition pattern and burn technique. To a limited extent, the crews have the capability (e.g., by adjusting ignition strip width) to increase the severity of a fire running too cold and to decrease the severity of an overly hot fire. This capability is important in achieving the fuel reduction objectives while minimizing damage to the duff and residual white pine. The extent of such capability is uncertain and varies according to specific situations. Rather than trying to represent this uncertainty for the specific site, which would provide few insights for a broader class of treatment decisions, we have chosen to model the compensation (or control) capability together with the range of acceptable burn intensities through a set of decision scenarios.

This latter characteristic—the acceptable burn intensity—is an additional site-specific characteristic. A burn too cold will not achieve the desired reduction in fine fuels, but the acceptable limit depends on the site characteristics and the objectives of the burn. In situations for which damage to duff or remaining overstory must be controlled, there is a threshold on the high-intensity side as well. The acceptable range can be represented by an interval, or "window," on the fireline intensity scale shown in figure 20. A burn whose intensity falls within this window produces minimum posttreatment costs. The potential costs caused by the fire hazard of the remaining fuels increase below the interval. The costs of damage to duff and, in the specific example, white pine, increase above the interval. This is a discrete-step approximation to a continuous relationship where effects are a function of intensity. Thus, the burn alternative is modeled as having four possible outcomes: the three just mentioned plus the chance of the fire escaping prescription and spreading into adjacent areas not scheduled for burning.

Using the representation just discussed, the intensity control capability is represented by specifying the acceptable range of predicted (without compensation) intensities, which, assuming effective compensation measures, will result in the actual intensity's falling within the acceptable range. The predicted intensity window is, therefore, as wide or wider than the actual intensity window, depending on the effectiveness of

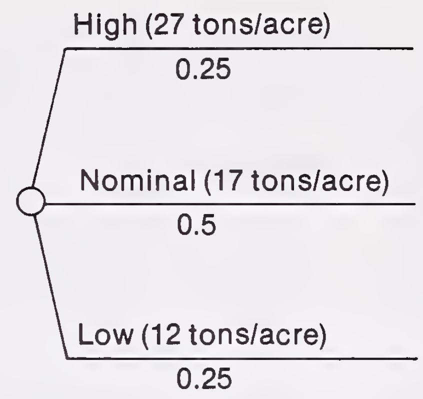


Figure 17.—Discrete representation of uncertainty in fuel load.

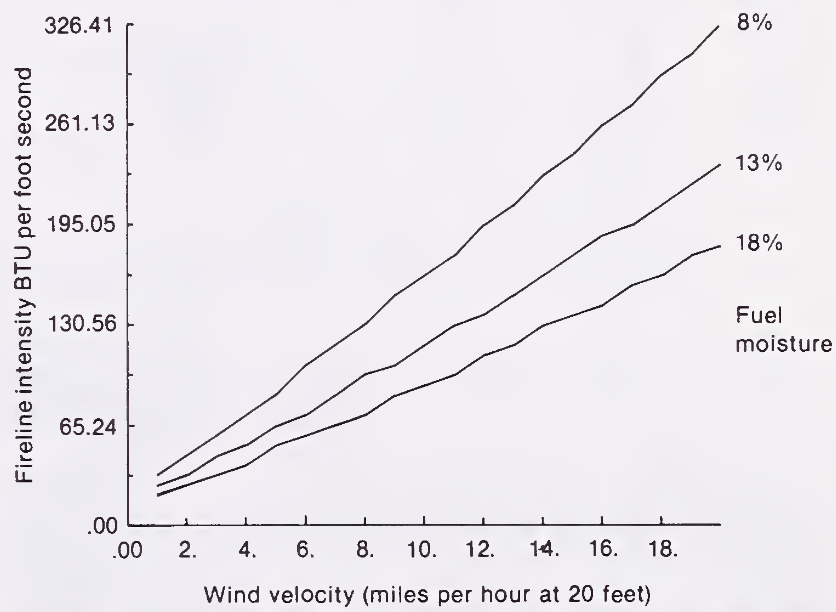


Figure 18.—Sample fire behavior model output for fine fuel loading of 27 tons per acre.

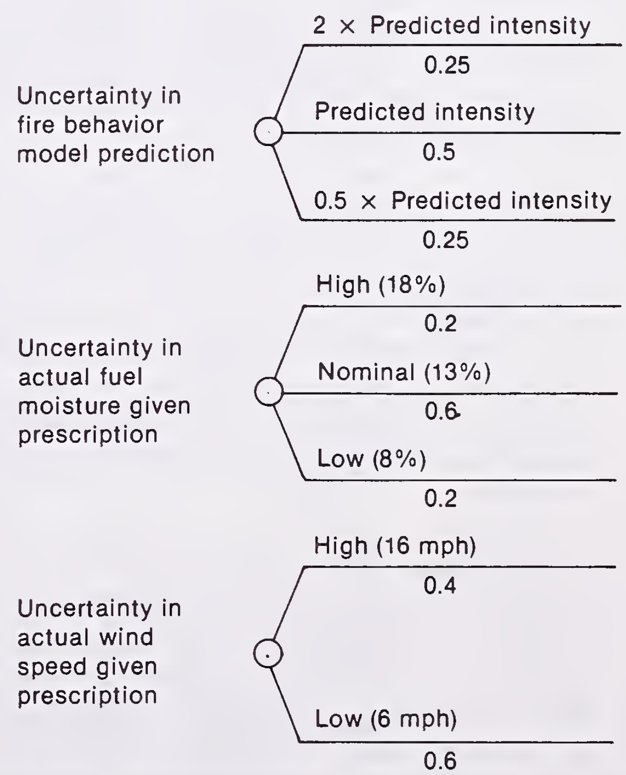


Figure 19.—Factors inducing uncertainty in fire intensity.

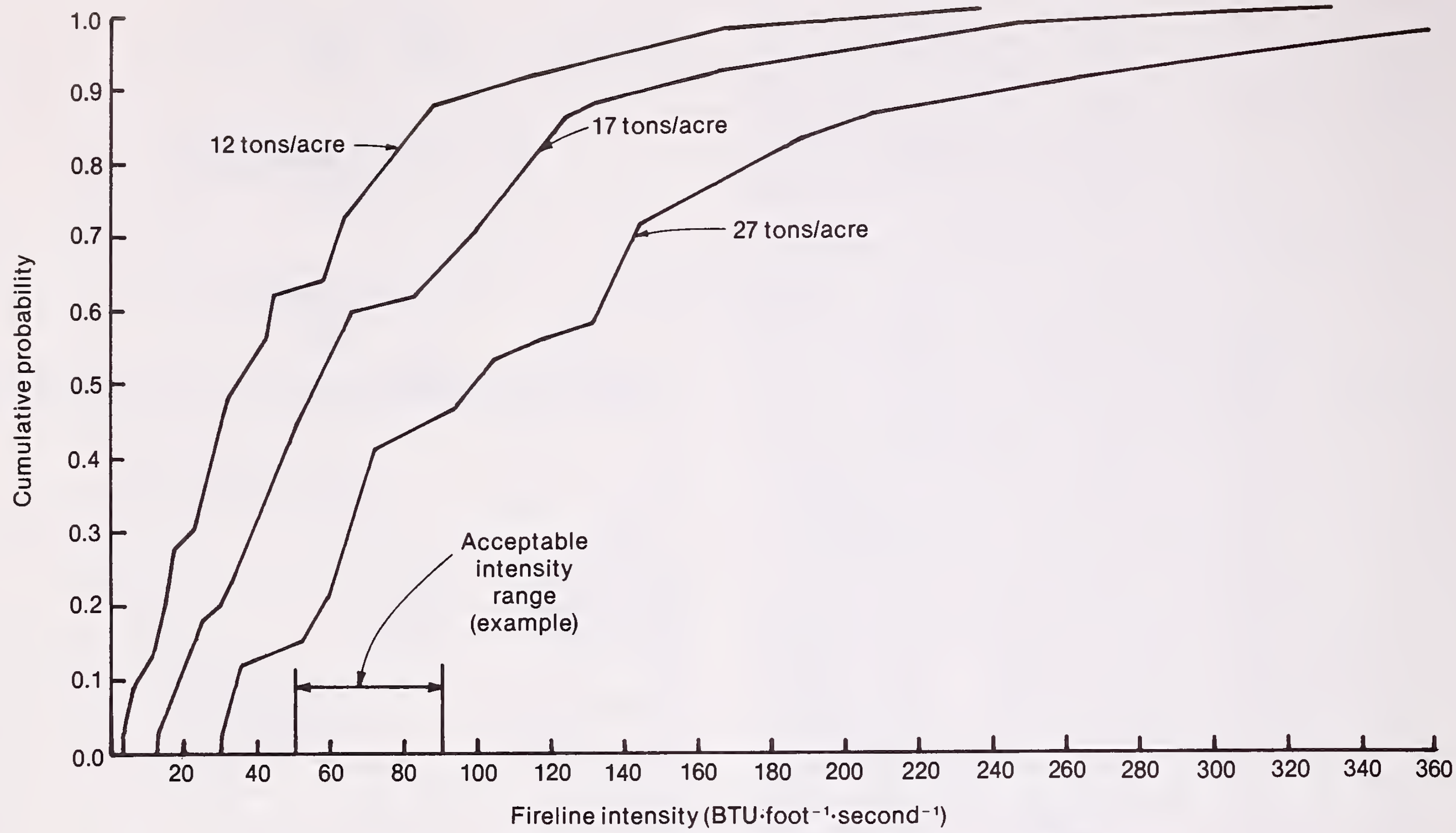


Figure 20.—Predicted intensity of prescribed fire given uncertainty in wind, fuel moisture, and fire behavior predictions (prior to burn compensation).

compensation measures. The four generalized decision scenarios used in this analysis are summarized in table 6a. The relationship between the four scenarios and the various combinations of acceptable intensity ranges and control capabilities is shown in table 6b. Essentially, we have tried to approximate a dozen specific scenarios through four generalized scenarios with progressively broader intensity tolerance ranges. The alternatives available are the same for each decision scenario: Should a broadcast burn, an intensive treatment, or no treatment be selected? Note that two specific combinations did not fall within any of the generalized scenario ranges listed in table 6a. These combinations were not addressed in the analysis.

Intensity windows associated with each decision scenario were superimposed on the three continuous probability distributions of figure 20 to produce the discrete distributions shown in table 7. Accurately predicting the chance of a fire escaping prescription is critical. To check this sensitivity, two modified scenarios (1a and 3a), incorporating a greater probability of escape, were created from decision scenarios 1 and 3. Outcome distributions for these two scenarios are listed in table 8.

Costs and Benefits.—The approach taken in assigning costs and benefits was to assume that the objective of the treatment decision is to minimize the costs and losses that must be subtracted from a constant, nominal level of benefit. Three cost categories were defined: the cost of implementing the selected fuel treatment (decision cost), the expected posttreatment cost from the potential fire hazard (fire hazard cost),

Table 6a.—Generalized decision scenarios for the fuel treatment decision

Scenario	Compensated (actual) acceptable intensity range ($Btu \cdot foot^{-1} \cdot second^{-1}$) Low end	High end
1 (narrow tolerance range)	50-55	95-100
2 (moderate tolerance range)	35-45	100-115
3 (wide tolerance range)	25-35	120-155
4 (very wide tolerance range)	20-25	170-225

Table 6b.—Relationships among decision scenarios[1]

Control capability	Acceptable range of actual intensities[2] ($Btu \cdot foot^{-1} \cdot second^{-1}$) Wide (40-100)	Nominal (50-90)	Narrow (60-80)
Can compensate for +/−5 mph wind speed	Scenario 3 [3](33-120)	Scenario 2 (42-180)	Scenario 1 (50-96)
Can compensate for +/−10 mph wind speed	--- (16-250)	Scenario 4 (20-225)	Scenario 4 (24-200)
Can compensate for +/−5% fuel moisture	Scenario 3 (25-140)	Scenario 3 (31-126)	Scenario 2 (38-112)
Can compensate for +/−5 mph wind speed and +/−5% fuel moisture	Scenario 4 (21-170)	Scenario 3 (26-153)	Scenario 3 (32-136)
No compensation capability	Scenario 2 (40-100)	Scenario 1 (50-90)	--- (60-80)

[1]*Decision scenarios are defined in table 6a.*
[2]*To minimize damage to remaining overstory.*
[3]*Acceptable range of predicted intensities prior to compensation ($Btu \cdot foot^{-1} \cdot second^{-1}$).*

and the cost from damage to the white pine seed trees (white pine cost). The white pine cost applies only to the prescribed burn alternative. The white pine stands are analogous to any resource present in a treatment decision problem that suffers increasing damage as the intensity of the prescribed burn increases. All costs are expressed in terms of dollars for the 25-acre site.

Fire hazard costs were calculated using the annual cost-plus-NVC model developed in the budget-level analysis. Suppression cost and resource value change data for this model are given in the appendix. Each fuel reduction outcome from the treatment decision (cold, nominal, hot, or escape for the burn alternative; and low, nominal, or high fuel reduction for the 6×6 YUM alternative) was represented by a posttreatment fire hazard class in the cost-plus-NVC model. For the burn alternative, these hazards correspond roughly to stylized fuel models 12 (medium slash), 11 (light slash), and 8 (closed timber litter) (Albini 1976). Output, given expected annual NVC for each hazard class, expressed on a per acre basis, was then scaled by the number of acres in the treatment site to estimate the annual expected fire losses for the site, given the treatment outcome. A 20-year stream of the expected annual values was then discounted to the present value to produce the nominal fire hazard costs. A discount rate of 10% was used. The nominal values, along with sensitivity ranges, are shown at the top of table 9. The costs of an escaped fire were similarly calculated by scaling the average cost of one such fire as calculated by the cost-plus-NVC model.

White pine damage costs are based on the assumption that the greater the intensity of a prescribed burn, the greater the pine mortality, which implies less capability of the white pine to initiate regeneration and necessary hand planting, reseeding, and fertilizing. Costs used (shown in table 9) are based on discussions with Clackamas District staff. The actual costs can vary from site to site. For this reason, several cost assumptions were examined in the value of information analysis discussed in the following paragraphs.

The decision costs were expressed earlier on a per-acre basis. For the entire 25-acre site, the estimated costs of carrying out each alternative are as follows:

No treatment	$ 2,500
YUM and burn	$20,000
YUM 6×6	$32,500

Analysis Under Uncertainty.—Analysis of the treatment decision produced a startling result: The no-treatment alternative was dominant, regardless of the decision scenario or cost assumption. This led to three possible conclusions:

1. There are benefits from fuel treatment considerably in excess of those explicitly quantified in this analysis.
2. Because of poor access, the costs of treatment for the studied site are much greater than for the average site.
3. Much more treatment activity is being carried out than is economically justified.

Table 7.—Probability distributions on outcome of prescribed burn, given fuel load and decision scenario

Scenario[1]	Outcome	Fuel loading: Low	Nominal	High
1	Cold	0.63	0.44	0.14
	Nominal	0.27	0.27	0.33
	Hot	0.10	0.28	0.46
	Escape	0.00	0.01	0.07
2	Cold	0.54	0.31	0.13
	Nominal	0.37	0.46	0.38
	Hot	0.09	0.22	0.42
	Escape	0.00	0.01	0.07
3	Cold	0.44	0.20	0.03
	Nominal	0.51	0.69	0.61
	Hot	0.05	0.10	0.29
	Escape	0.00	0.01	0.07
4	Cold	0.29	0.11	0.00
	Nominal	0.70	0.83	0.80
	Hot	0.01	0.05	0.13
	Escape	0.00	0.01	0.07

[1]*Decision scenarios are defined in table 6a.*

Table 8.—Outcome distributions for modified decision scenarios

Decision scenario[1]	Outcome	Fuel load: Low	Nominal	High
1(a)	Cold	0.62	0.44	0.14
	Nominal	0.25	0.25	0.32
	Hot	0.08	0.26	0.44
	Escape	0.05	0.05	0.10
3(a)	Cold	0.43	0.20	0.03
	Nominal	0.49	0.67	0.60
	Hot	0.03	0.08	0.27
	Escape	0.05	0.05	0.10

[1]*Created from generalized scenarios 1 and 3 of table 6a, allowing a greater probability of escape.*

Table 9.—Cost components (dollars/25 acres)

Outcome	Sensitivity range: Low	Nominal	High
		Fire hazard	
Cold (or low reduction)	500	1,000	5,000
Nominal	100	200	1,000
Hot (or high reduction)	50	100	500
Escape	15,000	30,000	75,000
		White pine[1]	
Cold	0	0	0
Nominal	1,500	3,000	15,000
Hot	7,500	15,000	75,000
Escape[2]	5,000	10,000	50,000

[1]*White pine damage costs are zero for all outcomes of the no treatment or intensive treatment alternatives.*
[2]*White pine costs given the escape outcome are relatively low to avoid double counting with the fire hazard costs.*

A hypothesis supporting conclusion 1 is that the cumulative effect of choosing the no-treatment alternative on a regular basis would be to greatly increase the expected fire hazard. To test this hypothesis, the cost-plus-NVC model developed for the budget analysis was again used. An extended period during which little fuel treatment was carried out would result in a considerably increased amount of area with a fire hazard represented by a slash type of stylized fuel model. This is reflected in the high slash case used in the budget level analysis. The per-site fire hazard (expected annual cost + NVC) is increased significantly by the cumulative effects of no treatment: The costs almost double. However, the increase is not enough to lead to another alternative's being preferable.

Another possible explanatory factor is that significant benefits accrue to fuel treatment as a result of considerations other than fire hazard reduction and seedbed preparation. These might include, for example, watershed and wildlife values, or enhanced esthetics.

It is often the case that the no-treatment option is unacceptable because of silvicultural regulations: The site is required to be restocked within 5 years. This should properly be considered a site-preparation decision rather than a fuel-treatment decision.

The second possible conclusion is clearly true as far as it goes, but decreasing the costs of the treatment alternatives (say, by 50%) does not change the dominance of the no-treatment alternative. The analysis showed that for one of the more intensive treatment alternatives to be optimal, all of the following must be true:

1. The cost of the treatment alternative must be lower by at least 50%.
2. The fire hazard costs must be at the high end of their range.
3. White pine damage costs (or other resources that may be damaged while carrying out fuel treatment) must be relatively low.

For the wide range of cases in which the no-treatment alternative is preferred, there is no value in reducing uncertainty in fuel load or in the outcomes of the other alternatives. For the purposes of the remainder of this analysis, it was assumed that some combination of conclusions 1 and 2 is descriptive of the situation. The no-treatment alternative was not considered further in the value of information analysis.

Value of Information Analysis

Figure 21 shows the decision tree on which the detailed analysis of the value of information was based. Note that the no-treatment option has been omitted. Probabilities for the outcomes given the burn alternative are not displayed; they depend on the decision scenario (tables 7 and 8).

Examination of the total nominal cost column of figure 21 highlights the difference between the two alternatives. The burn alternative is less expensive to

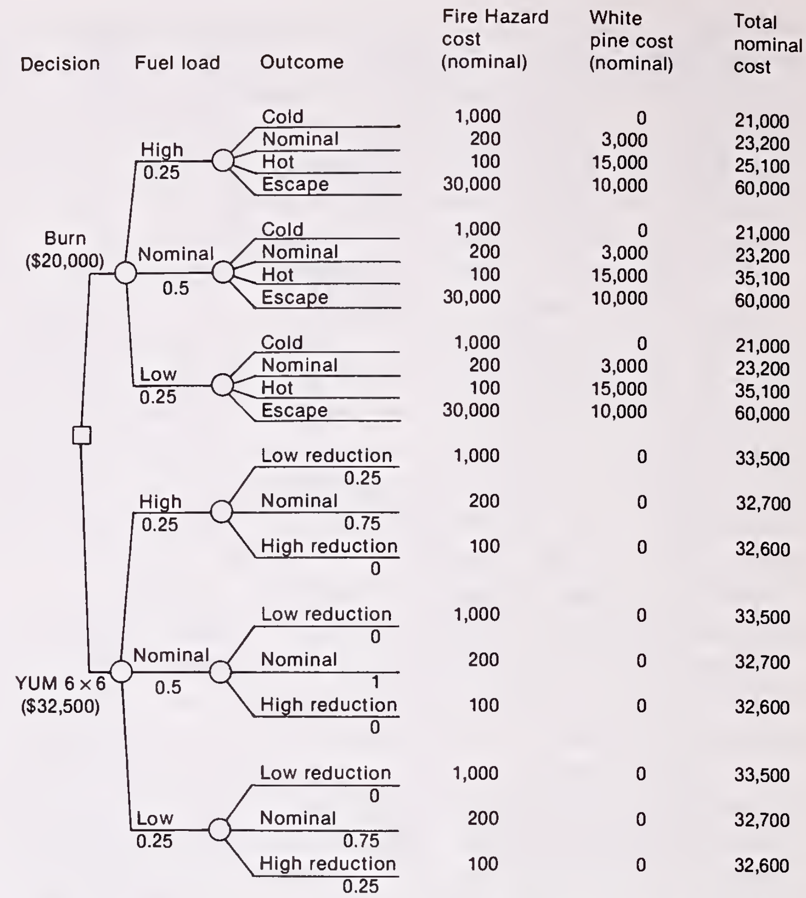


Figure 21.—Decision tree for treatment decision value of information analysis.

carry out and may have a relatively low cost outcome, but it may also have a very costly outcome; the variability in its cost is relatively high. In contrast, the variability in the cost of the intensive treatment alternative (YUM 6×6) is extremely low, but the initial (and minimum) cost is considerably higher. One must balance the uncertainty in one case with the known higher costs in the other. This is a natural situation in which to explore the economic value of reductions in uncertainty.

For all six decision scenarios using nominal costs, the preferred alternative is the broadcast burn. As the white pine or fire hazard costs increase or the decision costs decrease, the optimal alternative shifts to the intensive YUM treatment. The point at which the decision under uncertainty shifts depends on the decision scenario.

The value of information analysis was carried out by calculating the EVPI on postharvest fuel loading for each decision scenario while varying the fire hazard, white pine, and decision costs. Results of the analysis are summarized in figures 22a through 22d. In each figure, the EVPI on fuel loading is plotted on the vertical axis, while the cost component being varied is plotted on the horizontal axis. Figures 22a and 22b assume costs of the treatment alternatives as defined for the specific site under study. Treatment costs that are lower by 50% are assumed in figures 22c and 22d and may more accurately reflect a majority of fuel treatment decisions (because of the increased cost resulting from poor access to the specific site examined).

Figure 22a shows how the EVPI on postharvest fuel load varies among decision scenarios over a range of white pine damage costs. The results for scenario 2,

although not shown directly, are similar to those for scenario 1. The general pattern reflects the dominance of the burn alternative when white pine costs are low and the dominance of the intensive treatment alternative when white pine costs are very high. For intermediate cost levels the choice is not clear, thus the EVPI is greatest. The EVPI is nonzero at nominal white pine damage costs only for decision scenario 1a, for which it is assumed that the acceptable intensity range is narrow, control capability is limited, and the probability of fire escaping prescription is relatively high. As one moves from scenario 1 through 3 to 4, note that the EVPI decreases for white pine costs in the range of nominal to twice nominal. This is due to the increasing preference for the burn alternative as the acceptable intensity range and/or control capability increases. Finally, note that the cases with high escape probability (scenarios 1a and 3a) have lower maximum EVPI values but have greater EVPI (than scenarios 1 and 3) at the lower (and more realistic) cost levels.

In figure 22b, the EVPI on fuel loading is plotted against the posttreatment fire hazard costs. While the plots look considerably different, three patterns analogous to those of figure 22a are found. First, for all decision scenarios, the EVPI increases up to some point as the fire hazard cost component increases. Second, as the tolerance range for intensity assumed in the decision scenario increases (moving from scenario 1 to 4), the EVPI on fuel load decreases for a given level of fire hazard cost. Finally, assuming relatively high probabilities of a fire's escaping prescription (scenarios 1a and 3a) leads to an increase in the EVPI at the lower (and again more realistic) levels of the fire hazard cost.

Figure 22c shows the variation in fuel loading EVPI as white pine costs are changed for scenarios in which it is assumed that the costs of the treatment alternatives are one-half of the nominal (site-specific) values. (Specifically, YUM (8×10) and burn at $400 per acre or intensive (6×6) YUM at $600 per acre.) Scenarios 2 and 3 have plots similar to that for scenario 1. One immediately notices that both the maximum EVPI and the range of white pine costs over which the EVPI is nonzero are decreased from the nominal decision cost cases (fig. 22a). Of perhaps greater importance, the EVPI on fuel load for white pine damage costs of from one-half to one-and-one-half of nominal is considerably greater than was found for the nominal decision. At the nominal white pine damage cost level, EVPI on fuel loading ranged from about $200 to $1,000 for the 25-acre site, depending on the decision scenario. In this set of cases, with the costs of implementing the alternative treatment methods being perhaps closer to those found in a majority of treatment decisions, the scenarios with high probability of escaped fires have generally lower EVPI. This behavior reflects the dominance of the intensive treatment alternative when faced with such high escape probabilities. Better fuel information would only rarely change the decision.

EVPI on fuel loading as a function of fire hazard cost for the case with lower decision costs is shown in figure 22d. Again, scenario 2 is similar to scenario 1. It is interesting to contrast these plots with those for the nominal decision costs in figure 22b. The maximum EVPI is achieved at much lower assignments of fire hazard cost for each decision scenario. In particular, the value of perfect information at the nominal fire hazard cost point is significant, ranging from $500 to $1,000 for the basic scenarios. The modified scenarios (with higher probability of a fire's escaping prescription) result in generally lower EVPI values, reflecting the dominance of the low-variance, intensive treatment option for such scenarios. In comparison with figure 22c, one notes that the EVPI is relatively high for a wide range of hazard costs in figure 22d. Fire hazard cost is a major consideration regardless of the alternative chosen, while white pine damage is risked only for the burn alternative.

The Value of Imperfect Information

The information values discussed above represent the expected values of perfect information. Equivalently, the EVPI gives the economic value of totally eliminating the uncertainty inherent in the information of the fuels management specialist. Clearly, such a complete elimination of uncertainty is impossible (or at least very expensive) in the context of postharvest loading of fine fuels.

To investigate the value of reducing—but not eliminating—uncertainty, EVPI was calculated on fuel load for a variety of cases in which the variance in the initial probability distribution was reduced by about 60%. This led to EVPI values in the range of 30-50% of those plotted in figures 22a through 22d. The variation in EVPI with respect to the decision scenarios and cost components was analogous to the original cases.

This analysis suggests that the value of improved but not perfect information might be on the order of one-half to two-thirds of the EVPI. Such reduced information values are most appropriate for use in guiding the allocation of information-gathering resources.

Summary and Recommendations

For the site-specific decision as orginally defined, the no-treatment alternative was clearly dominant. Even when the costs of treatment are reduced by half, to levels that more closely approximate many treatment decisions, the no-treatment alternative is still preferable. For the reduced treatment cost decision problem, decreasing fire hazard or white pine damage costs could lead to one of the treatment options being superior.

In light of the above observations, more research is necessary to either:

1. Determine the cumulative fire hazard cost, wildlife benefits, or other factors that justify carrying out fuels treatment activities on a majority of harvest sites, or

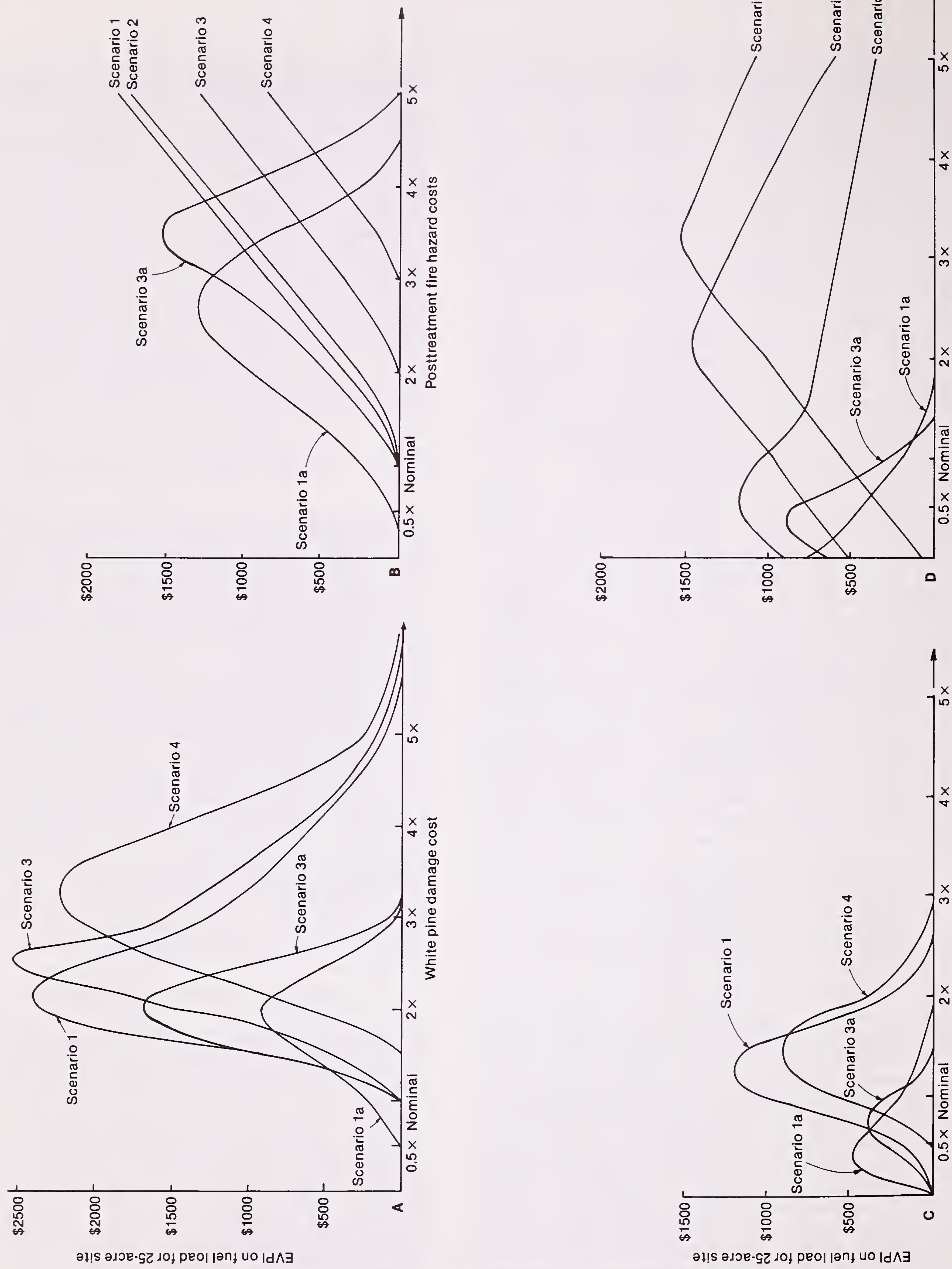


Figure 22.—EVPI on fuel load, (A) as a function of white pine cost; (B) as a function of fire hazard cost; (C) as a function of white pine cost, for scenarios with one-half nominal treatment costs; and (D) as a function of fire hazard cost, for scenarios with one-half nominal treatment costs. Scenarios are defined in tables 6a and 8.

2. Demonstrate that the values defined in (1) are insufficient to justify, on an economic basis, the amount of fuel treatment activity presently being done.

In treatment decisions for which the no-treatment alternative is not dominant (or when it has been decided that some treatment is necessary, based on other factors), some effort devoted to gathering information on postharvest fuel load may be worthwhile. Using the most likely scenarios, the expected value of perfect information on fuel load fell between $300 and $800 for a 25-acre site ($12 to $32 per acre). Information that could be expected to reduce uncertainty (perhaps reducing the variance of the probability distribution on the loading of fine fuels by 50-75%) would be worth $100 to $400 ($4 to $16 per acre). Accounting for all costs, this suggests that in many cases it would be worthwhile to invest one to two person-days in developing an improved estimate of postharvest fuel load before making the final treatment decision.

It is worth noting that improved information could have value beyond reducing uncertainty in the aggregate mass of fine fuels. Better understanding of the breakdown of fuels by size class and type could be used as input to an improved fire behavior model to obtain better predictions of the characteristics of prescribed fires. The same information would also be useful in carrying out the treatment option ultimately selected and in assessing the effectiveness of treatment.

The recommendations derived from this study can be summarized as follows:

1. Careful thought should be given to the no-treatment alternative in more instances. Improved exchange of information among fuel management, silviculture, wildlife, recreation, and other specialists would help in resolving this issue.
2. For harvest sites having important resources that are sensitive to damage from a burn or for sites having poor access leading to high treatment costs, the more expensive hand treatment options may be worthwhile.
3. For the many cases in which broadcast burning is likely to be a good alternative but for which some resource values may be sensitive to excessive high or low burn intensities, it is probably worth investing one or two person-days in improving the fuel information base prior to making the final treatment decision.

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APPENDIX

BASE CASE AND SENSITIVITY DATA

General

The following data represent the Clackamas and Estacada districts of the Mount Hood National Forest:

Nominal budget	*(dollars/year)*
Prevention	58,000
Presuppression and initial attack	208,000
Fuel treatment and brush disposal	477,000
Total	743,000
Ignitions	*(average number/year)*
Industrial	1
Other human-caused	25
Lightning	8
Nominal area distribution: fuel types	*(acres)*
Total area	400,000
Timber litter plus understory (model 10)	280,000
Timber litter (model 8)	80,000
Heavy slash (model 13)	20,000
Medium slash (model 12)	20,000

Intensity Distribution

Table A-1 gives the discrete probability distributions for fireline intensity (Byram 1959) given the fuel model type in which a fire starts. Intensity classes are defined as follows:

Intensity class	Btu·foot^{-1}·second^{-1}
Low	0–100
Medium	100–700
High	>700

The data in the table are based on the cumulative probability distributions generated by the Rothermel (1972) fire behavior model using historical weather data (Furman and Brink 1975) for the case study area. (A sample model run is shown in fig. A-1.)

Table A-1.—Probability distributions for fireline intensity class given fuel type at fire origin

Area type of fire start	Intensity class: Low	Moderate	High
Heavy slash (13)	0.00	0.28	0.72
Medium slash (12)	0.03	0.61	0.36
Timber litter (8)	1.00	0.00	0.00
Litter + understory (10)	0.78	0.19	0.03

Escape Fractions

The fraction of fires escaping initial attack (or, equivalently, the probability that a fire escapes) is conditional on fireline intensity. The following escape fractions are based on the judgment of Mount Hood fuels and fire management staff: low intensity, 0.0; moderate intensity, 0.3; and high intensity, 0.8.

Size Distribution

Table A-2 gives the individual probability distributions for fire size class, given area type (stylized fuel model type) at the fire's origin, intensity class, and escape/control status. The distributions are based on the judgment of Mount Hood fuels and fire management staff. An iterative process was used whereby the implications of an initial set of distributions were examined to refine the assessments.

Resource Value Changes

Expected changes in resource value caused by fire are listed in table A-3, expressed in terms of dollars per acre. Values given are based primarily on timber resources and cost of rehabilitation; implications of assigning greater values based on nonmarket

resources are examined in the sensitivity analysis and value of information subsections. Timber values and rehabilitation costs used are based on recent experience of the Mount Hood National Forest.

NVC values are a function of fire size, intensity, and location. Fires in the lowest intensity range have very low expected value changes. Small fires starting in slash are also assigned small values, as such fires have little resource impact. Larger fires starting in slash areas are expected to have spread into timber, implying greater timber damages.

Table A-2.—Fire size probability given area type and intensity class

Fire type / Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
Controlled fires	All area types			
Low	0.95	0.05	0.00	0.00
Moderate	0.80	0.20	0.00	0.00
High	0.60	0.40	0.00	0.00
Escaped fires	Area type: Heavy slash (13)			
Low	0.20	0.80	0.00	0.00
Moderate	0.10	0.70	0.19	0.01
High	0.00	0.80	0.18	0.02
	Area type: Medium slash (12)			
Low	0.40	0.60	0.00	0.00
Moderate	0.20	0.60	0.19	0.01
High	0.00	0.80	0.18	0.02
	Area type: Timber litter (8)			
Low	1.00	0.00	0.00	0.00
Moderate	0.20	0.60	0.20	0.00
High	0.00	0.80	0.19	0.01
	Area type: Litter + understory (10)			
Low	1.00	0.00	0.00	0.00
Moderate	0.20	0.60	0.19	0.01
High	0.00	0.80	0.18	0.02

Table A-3.—Expected resource value changes in dollars per acre

Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
	Area type: Heavy slash (13)			
Low	200	200	200	200
Moderate	500	500	1,000	1,000
High	500	750	1,200	1,200
	Area type: Medium slash (12)			
Low	200	200	200	200
Moderate	500	500	1,000	1,000
High	500	750	1,200	1,200
	Area type: Timber litter (8)			
Low	200	200	200	200
Moderate	1,000	1,500	1,500	1,200
High	1,500	2,000	2,000	2,000
	Area type: Litter + understory (10)			
Low	200	200	200	200
Moderate	1,000	1,500	1,500	1,200
High	1,500	2,000	2,000	2,000

Suppression Costs

Suppression costs for fires escaping initial attack are shown in table A-4. These costs are based on experience of the Mount Hood and other forests in the Pacific Northwest Region. It is assumed that all fires of the smallest size class are controlled by initial attack forces. Costs are given in average dollars per acre per fire.

Table A-4.—Expected suppression costs for fires that escape initial attack (dollars per acre)

Intensity class	Size class: 0.1 average acres	10 average acres	100 average acres	1,000 average acres
Low	0	500	500	500
Moderate	0	500	500	500
High	0	500	500	500

Sensitivity Test Data

Table A-5 shows the distribution of area among the four fuel types for three fuel scenarios: high slash, nominal slash, and low slash. In table A-6, fireline intensity distributions are given for scenarios involving twice-nominal intensities and half-nominal intensities.

Table A-5.—Distribution of land area (thousands of acres) among the four fuel model types for three fuel scenarios

Fuel scenario	Fuel model type: 13	12	8	10
High slash	40	80	200	80
Nominal	20	20	280	80
Low slash	10	10	280	100

Table A-6.—Intensity class probabilities for fire behavior scenarios involving twice-nominal and half-nominal fireline intensities

Area type of fire start	Intensity class: Low	Moderate	High
Intensity distribution with two times intensities			
Heavy slash (13)	0.05	0.41	0.54
Medium slash (12)	0.13	0.60	0.27
Timber litter (8)	1.00	0.00	0.00
Litter + understory (10)	0.81	0.17	0.02
Intensity distribution with one-half times intensities			
Heavy slash (13)	0.00	0.14	0.86
Medium slash (12)	0.01	0.48	0.51
Timber litter (8)	0.50	0.50	0.00
Litter + understory (10)	0.39	0.48	0.13

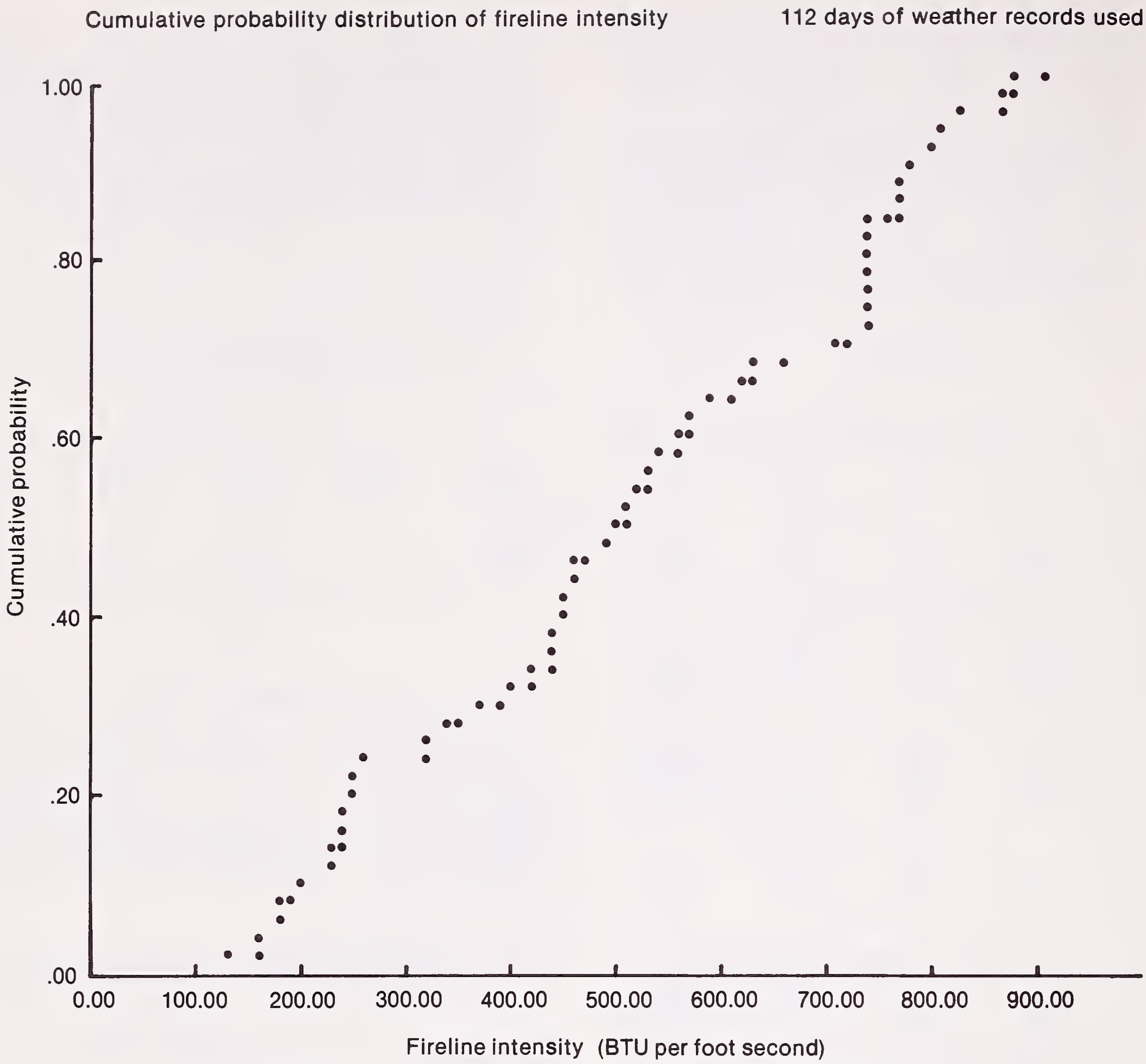

Figure A1.—Sample FIREBHV output (fuel model 12, Ripplebrook Fire Weather Station).

Barrager, Stephen M., David Cohan, and Peter J. Roussopoulos. 1982. The economic value of improved fuels and fire behavior information. USDA Forest Service Research Paper RM-239, 32 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

The development and case study application of a method for determining the economic value of improving fuel and fire behavior information for fire management decisionmaking is presented. Two routine decisions are analyzed on the Mount Hood National Forest—the annual fire management budget request and a site-specific fuel treatment decision.

Keywords: Decision analysis, wildfire protection, economic efficiency, fuel treatment, prescribed fire

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Rocky Mountains

Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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